III.—*On the Dynamics of Earthquakes; being an Attempt to reduce their observed Phenomena to the known Laws of Wave Motion in Solids and Fluids. By* ROBERT MALLET, ESQ., *Mem. Ins. C. E., M. R. I. A., Pres. Geol. Soc. Ireland, &c.*

Read 9th February, 1846.

THE present Paper constitutes, so far as I am aware, the first attempt to bring the phenomena of the earthquake within the range of exact science, by reducing to system the enormous mass of disconnected and often discordant and ill-observed facts which the multiplied narratives of earthquakes present, and educing from these, by an appeal to the established laws of the higher mechanics, a theory of earthquake motion.

If I shall have in any degree succeeded in this, I must believe that a considerable advance will have been made in one of the most important, but, up to this time, one of the most absolutely unsystematized and unscientific regions of physical geology.

If the foundation for such a theory be really laid, it must become the means of guiding and directing future observers during earthquakes; enabling them to pass by that which is accidental, and to apply right methods and suitable instruments in ascertaining the really important elements of their motions in measures of time and space, &c., by which hereafter the narratives of earthquakes, ceasing to be merely scrolls written "with mourning and lamentation and woe," may become systematized records of facts, which a true theory shall render available, and in the highest degree valuable, for the advancement of terrestrial physics and geology.

My speculations upon earthquake motion commenced with an attempt to unravel and explain a single partial and minute phenomenon occasionally observed

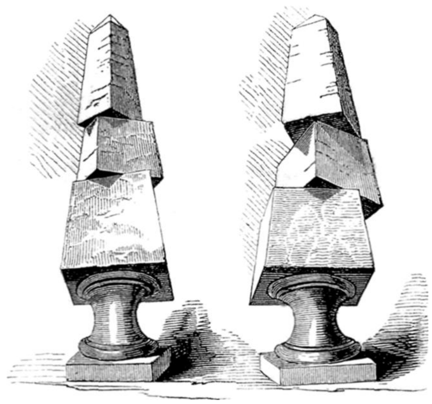
in these convulsions, and of which I felt convinced that a false explanation, so far as any, had been previously given.

I have followed, in the subsequent pages, rather the course of my own progress than a strictly systematic arrangement, and shall therefore commence with the explanation of the phenomenon above alluded to, and which led me to the subsequent investigation and results.

The phenomenon alluded to, is the displacement of the separate stones of pedestals or pinnacles, or of other portions of the masonry of buildings, by the motion of earthquakes, in such a manner that the part moved presents evidence of having been twisted upon its bed round a vertical axis. This has been hitherto attempted to be explained by assuming a vorticose motion to occur. The first notice I find recorded of such a peculiar motion is in the Philosophical Transactions, in an account of the earthquake at Boston, in New England, of November 18th, 1755, communicated by John Hyde, Esq., F. R. S. He says: "The trembling continued about two minutes. Near 100 chimneys are levelled with the roofs of the houses, and many more shattered." "Some chimneys, though not thrown down, are dislocated or broken several feet from the top, and partly turned round, as on a swivel." "Some are shoved to one side horizontally, jutting over, and just nodding to fall, &c. &c." This author does not seem to have been struck with the odd circumstance of the twisting round of the chimneys, and offers no explanation.

The next instance that I have found is in the account of the great earthquake of Calabria, in 1783, as recorded by the Royal Academy of Naples, quoted by Mr. Lyell, in his Principles of Geology, vol. i. p. 482, 2nd edit. After describing several other remarkable phenomena, tending to show the great velocity of the shock, such as, that many large stones were found, as it were, *shot out* of their beds in the mortar of buildings, so as to leave a complete cast of themselves in the undisturbed mortar, while, in other instances, the mortar was ground to powder by the transit of the stone, he says: "Two obelisks" (of which he has given figures), "placed at the extremities of a magnificent façade in the convent of St. Bruno, in a small town called Stephano del Bosco, were observed to have undergone a movement of a singular kind. The shock which agitated the building is described as having been horizontal and vorticose. The pedestal of each obelisk remained in its original place, but the separate stones above were turned

partially round, and removed sometimes nine inches from their position, without falling." This is all that Lyell says upon the subject; he contents himself, apparently, with the vorticose account of the Neapolitan Academy.

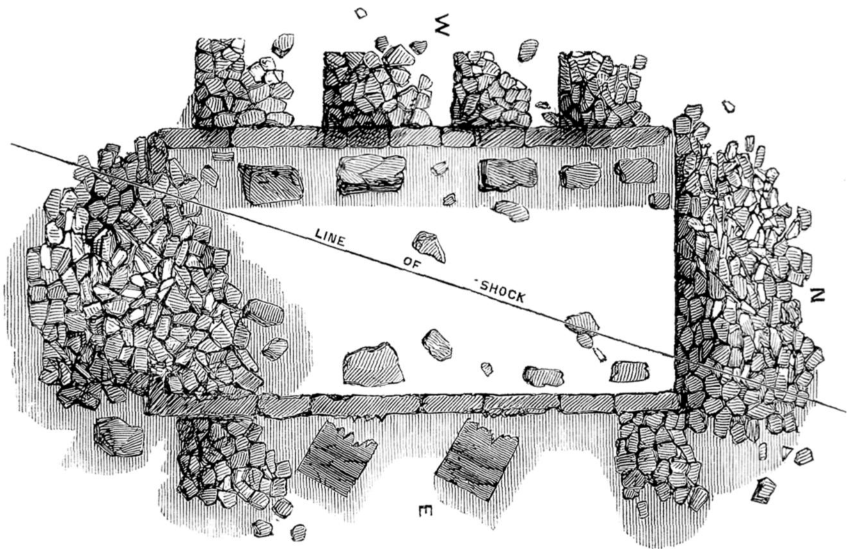


I have found some few other notices of similar phenomena in old books of travels; two additional instances, however, will be sufficient. The first will be found in the Quarterly Journal of the Royal Institution, in a narrative of the earthquake in Chili, of November, 1822, communicated by F. Place, Esq.

The Church of La Merceda, at Valparaiso, stood with its length north and south, built of burned bricks (the houses are built of *adobes*, or sun-dried bricks). "The church tower, sixty feet high, was levelled." "The two side walls, full of rents, were left standing, supporting part of the shattered roof, but the two end walls were entirely demolished. On each side of the church were four massive buttresses, six feet square, of good brick-work; those on the western side were thrown down, and broken to pieces, as were two on the eastern side. The other two were *twisted off from the wall*, in a north-easterly direction, and left standing."

The direction of the shocks was thought to be from the south-west or from the north-west. We shall see hereafter evidence, in the twisting of the two remaining buttresses, that the former was the real direction of the shocks, and that there was no vorticose motion (indeed the very idea of two vortices, with centres only a few feet apart, is absurd upon the face of it), but that the twisting

of the buttresses is to be accounted for simply by a straight line movement, acting in connexion with the attachment of the buttresses at one side to the flank wall of the church.



The last instance I shall quote is from the pages of the able and delightful Darwin, in his Journal of a Naturalist's Voyage.* In describing the effects of the great earthquake of March, 1835, upon a building in the town of Conception; and, after noticing the evidences of immense velocity in the shock, by which the buttresses, projecting from the nave walls of the cathedral had been cut clean off close to the wall by their own inertia, while the wall, which was in the line of shock, remained standing, he proceeds: "Some square ornaments on the coping of these same walls were moved by the earthquake into a diagonal position. A similar circumstance was observed after an earthquake at Valparaiso, in Calabria, and other places, including some of the ancient Greek temples (for which he quotes Arago in l'Institut., 1839, p. 337, and Miers' Chili, vol. i. p. 392). "This twisting displacement," he proceeds, "at first appears to indicate a vorticose movement *beneath each point* thus affected, but this is highly improbable."

* Colonial Library Edition, p. 308.

"May it not," he adds, "be caused by a tendency in each stone to arrange itself in some particular position, with respect to the lines of vibration, in a manner somewhat similar to pins on a sheet of paper when shaken?"

The sagacity of Darwin shewed him that the vorticose hypothesis was improbable, and that in order to its being at all tenable, a separate vortex must be admitted for every separate stone found twisted, the axis of rotation of the vortex having been coincident with that of the stone. Besides this paramount improbability, therefore, a little further reflexion would have led either Lyell or Darwin to estimate the inconceivable angular velocity of motion at the extremity of the radius of one of these vortices, even if assumed at no more than a few hundred feet, necessary, in order that its velocity within a few inches of the centre should be so great as to wrench out of its mortared bed, and twist, a block of masonry, by merely its own inertia.

On lately reading the foregoing passage of Darwin, I was soon led to see that the twisting phenomenon observed could be readily accounted for upon the established principles of mechanics, without having recourse to either vortices or vibrations arranging blocks of many hundred weights after the manner of pins on paper, or sand on one of Chladni's acoustic plates, an explanation which appears quite as far from probability as its predecessor.

I assume nothing more than what is universally admitted,—that during earthquakes a motion of some sort takes place, by which the ground itself, and all objects resting upon it, are shaken, or moved back and forwards by an alternate horizontal motion, within certain narrow limits, which, for all present evidence to the contrary, may be a straight line motion, though possibly variable in direction at different and sometimes closely successive times, and the velocity of which is sufficient to throw down, or disturb the position of bodies supported by the earth, through their own inertia.

If a stone, whether symmetrical or otherwise, rest upon a given base, and that motion be suddenly communicated horizontally to that base in any direction, the stone itself will be solicited to move in the same direction. The measure of force with which the movement of the base is capable of affecting the stone or other incumbent body is equal to the amount of friction of the latter upon its base, a function of its weight, which, without the intervention of cement, may be from one-fifth to one-tenth of the weight of the body, for cut stone resting on

cut stone, but may be increased to any amount by the intervention of cement. The stone, however, is possessed of weight, and therefore of inertia, that is to say, being at rest, its whole mass cannot be instantly brought into motion by the plane on which it rests; and if the amount of adhesion between the stone and its bed be less than the inertia due to any given velocity of horizontal movement of the bed, the bed will move more or less from under the stone, or the stone will appear to move in a contrary direction to that of the motion of its bed.

Now the inertia of the stone, which is here the resisting force, may be considered to act at its centre of gravity. The impelling force is the grasp of the stone which its bed holds of it by friction or adhesion, and this may also be referred to some one point in the surfaces of contact, which we may call *the centre of adherence.*

If, then, a stone, or other solid, rest upon a plane which is suddenly moved with sufficient velocity to produce motion in the incumbent body, three several conditions of motion of the body may occur, according to the respective positions of its centre of gravity and of the centre of adherence.

1st. The centre of gravity of the body may be at such a height above the base that it shall upset by its own inertia. This is the case with houses, towers, walls, &c. &c., when they fall by earthquakes, accompanied, however, by dislocation of their parts.

2nd. The centre of adherence may be in a point of the base plumb under the centre of gravity of the body, or in a vertical plane passing through its centre of gravity, and in the direction of motion of the base.

In this case the stone will appear to move in the opposite direction to that in which the base has moved, that is to say, the body may have acquired more or less the direction of motion of the base, according as the motion of the latter has been of longer or shorter continuance, or less or more rapid; but in so far as the movement in opposite directions has taken place, the base in reality has slipped from under the body.

3rd. The centre of adherence may neither be plumb under the centre of gravity of the body, nor in the plane of motion passing through its centre of gravity, but in some point of the base outside the line of its intersection by the plane; in which case the effect of the rectilinear motion in the plane of the base will be to twist the body round upon its bed, or to move it laterally, and twist it at the

same time, thus converting the rectilinear into a curvilinear motion in space. The relative amount of the two compounded motions being dependent upon the velocity and time of movement of the base, and upon the perpendicular distance measured horizontally at the surface of adherence between the centre of adherence and the centre of gravity of the body.

This latter case is that which appears to have twisted the stones of Calabria, South America, and Greece, and affords, as I feel assured, the true explanation of the phenomenon.

The relations of these forces, which have taken so many words to state correctly, might, of course, have been expressed algebraically in three lines, but as this would not be universally intelligible, I have preferred the more tedious and inelegant statement of words, and, to render the matter quite familiar, have prepared a model of one of the Calabrian pedestals figured by Mr. Lyell, which will exhibit to the eye all the phenomena already adverted to, on communicating by the hand a rectilinear horizontal motion to the base.*

I have now proved that no vorticose motion is requisite to account for the twisting of bodies, as observed in earthquakes; that nothing more than a simple horizontal rectilinear motion is demanded. But it may be asked, if this motion in earthquakes be also an alternate one—if the earth shake both back and forwards—how is it that these and other displaced bodies are not replaced by the reverse motion—by the same sort of motion acting in the contrary direction?

This question is, I believe, fertile in consequences, and its consideration has led me to some further conclusions as to the nature of earthquake motion. After looking through a great number of authors on earthquakes I have not been able to find one that has endeavoured, far less succeeded, in shaping to himself any distinct notion as to what the precise nature of the earthquake movement is. The ancients, appealing to their senses, so far as these could guide them, thought that it was like the shaking of a sieve, as the word σεισμος tells us. The moderns, in general, are not more exact in their notions; "a trembling"—"a vibration"—"a concussion"—"a movement," and soforth, are the words we find scattered through even scientific authors: Michell, Lyell, Darwin, with some others, although they obviously have formed no distinct idea on the subject, use the

* The model was exhibited to the Academy.

word "undulation," and, in so far, have come nearer to the truth; for it appears to me that the fact that displaced bodies are not occasionally replaced in earthquakes, is conclusive evidence of either one of two things:—either the motion is limited to horizontal, direct movement in one or more directions, and, if so, the whole mass of the disturbed country must be pushed bodily forward, and remain so, of which there is no evidence; and all bodies must, as the effect of one shock, fall in the one direction, and not in opposite directions, which is contrary to observed facts: or, on the other hand, if the movement be an alternate, horizontal motion, as all observations go to prove it is, then the motion in one direction must be slower than in the other; or attended with other differences of circumstances; the backward motion must be different from the forward motion, or otherwise displaced bodies would be sometimes replaced by the recurrence, in the opposite sign, of forces similar and equal to those that first set them in motion: but they are not found so replaced.

Now, of all conceivable alternate motions, the only one that will fulfil the requisite conditions observed, namely, that shall move with such an immense velocity as to displace bodies by their inertia, or even shear close off great buttresses from the walls they sustained, or project stones out of their beds by inertia,—that shall have a horizontal, alternate motion, either much quicker in one direction than in the other, or different in its effects, and that shall be accompanied by an upward and downward motion at the same time (a circumstance universally described as attendant on earthquakes);—the only motion that will fulfil these conditions, is *the transit of a wave of elastic compression, or of a succession of these, in parallel or in intersecting lines, through the solid substance and surface of the disturbed country.*

The idea that earthquake motion consists of a wave of some sort is not new, although so entirely neglected by the great mass of recent geological authors. To the Rev. John Mitchell, M. A., Fellow of Queen's College, Cambridge, the merit of this idea appears to be due. In a paper communicated to the Royal Society, read in 1760,* he treats at length of the origin and phenomena of earthquakes, and distinctly enunciates the following views:

That the motion of the earth is due to a wave propagated along its surface

* Phil. Trans. vol. li. part 2.

from a point where it has been produced by an original impulse. This impulse he conceives to arise from the sudden production or condensation of aqueous vapour, under the bed of the ocean, by the agency of volcanic heat, the supposed mechanism of which he minutely describes. He supposes the crust of the earth either to float on liquid matter, so that undulations would be easily propagated through the former, or to float upon vast pent-up receptacles of aqueous vapour; and he proceeds: "As a small quantity of vapour, almost instantly generated at some considerable depth below the surface of the earth, will produce a vibratory motion, so a very large quantity (whether it be generated almost instantly or in any small portion of time) will produce a wave-like motion. The manner in which this wave-like motion will be propagated may, in some measure, be represented by the following experiment. Suppose a large cloth or carpet (spread upon a floor) to be raised at one edge, and then suddenly brought down again to the floor, the air under it being, by this means, propelled, will pass along till it escapes at the opposite side, raising the cloth in a wave all the way as it goes. In like manner, a large quantity of vapour may be conceived to raise the earth in a wave, as it passes along between the strata, which it may easily separate in an horizontal direction, there being little or no cohesion between one stratum and another." His views, at length, may be found in his paper in the Phil. Trans. vol. li. sec. 58, &c. &c.

Michell wholly mistook the nature of the wave itself; and the existence of such a wave as he assumes is totally inconsistent with the phenomena of earthquake motion, as recorded by himself and others; and the mechanism which he imagines to account for the origin of his wave, and its propagation through the floating crust, is inconsistent with the conditions essential to that order of wave which the ascertained phenomena of earthquakes shew to be the true one.

Michell also states, that the great waves of the sea, which frequently succeed the shock of earthquakes, and roll to shore at an enormous height and velocity, are due to the same cause, namely, an undulation given to the ocean water, at a point directly above that at which the primary terrestrial undulation takes place. He considers that the greater earthquakes have their centre of effort generally, if not always, under the ocean, and proposes to determine the position of this centre, in any case, by observation of the direction of these great waves, and the times at which they reach several distant shores, illustrating his view by such a

calculation respecting the waves that rolled upon the shores of Europe, Great Britain, Madeira, and the West Indies, &c., at the great Lisbon earthquake in 1755.

He finds that these waves, if produced at a point indicated by their respective directions of motion, and situated some thirty leagues or so at sea, about midway between Oporto and Lisbon, must have diverged thence with very different velocities, to have reached these several shores at the observed times; and this he accounts for by asserting that "the true reason of this disproportion in the velocity of the waves seems to be in the difference of the depth of water through which they had passed;" those moving most rapidly which passed over the deep ocean, and those most slowly that entered the shallower seas or estuaries.

The latter conclusion shows the highest acumen in the author, writing at a time when the laws of tidal waves were so ill understood, and had engaged so little attention.

To return to the question, why are displaced bodies (such as the stones of the Calabrian obelisks) not replaced, more or less completely, by the back stroke, or return motion, of the wave?

Starting from the proposition that earthquake motion consists in the transit of an elastic wave, or a succession of these, through the solid crust of the globe, produced by *any* original impulse, which may be either percussive, as when vast masses of rock suddenly give way, and are broken up by the pressure of elastic or liquid matter from below, or such as operates (if it were possible, as Michell assumes) when vast cavities, filled with high-pressure steam, or water in an incandescent state, are broken up, and the steam instantly condensed, and its place supplied with cold water, producing a shock, such as we observe on a minute scale when steam is blown from a pipe into cold water; or of the nature of that called into action when masses of material, resisting the ventage of volcanoes, are at last blown away, and produce a mighty recoil by the explosion, as in the case recorded by Humboldt, of a mass of rock weighing above two hundred tons, which was shot from the crater of Cotopaxi to a distance of nine miles; which of these, or what other sufficient cause, whether existing in nature or not, may be assigned for the original impulse, it is unnecessary for us here to consider: only let an impulse of some sort be granted, and we are to follow out its consequences according to the known laws of waves or pulses in æriform, liquid, and solid bodies.

First, then, the original impulse may either be on land, as in a volcanic region, situated in the heart of a great continent or island, or it may be beneath the bed of the ocean. The former case is that of South America, where, in the volcanic region of the Andes, earthquakes are of almost daily occurrence, most of them, however, not of great power or extent.

The latter case seems to be that, which almost universally belongs to great earthquakes; their origin is beneath the ocean, and that this should be so is probable when we consider that the force and extent of the shock must depend upon the resistance overcome by the original impulse, which will probably be always far greater when the crust of the earth is ruptured beneath the deep ocean, and under its profound masses of deposited materials, than on elevated land, where the already formed continents are provided with safety valves in the acting volcanoes.

Now, when the original impulse comes from the land, an elastic wave is propagated through the solid crust of the earth and through the air, and transmitted from the former to the ocean water, where the wave is finally spent and lost.

When, on the other hand, the original impulse comes from the bed of the deep ocean, three sorts of waves are formed and propagated simultaneously, namely, one, or several successively through the land, which constitutes the true earthquake shock or shocks; and coincident with, and answering to every one of these, one or more waves are formed and propagated through the air, which produce the sound like the bellowing of oxen, the rolling of waggons, or of distant thunder, accompanying the shock; and a third wave is formed and propagated upon the surface of the ocean, which rolls in to land, and reaches it long after the shock or wave, through the solid earth, has arrived and spent itself.

The plan, or horizontal outline of each of these waves, will be more or less circular or elliptical at first, according as the origin or centre of disturbance is at a single point, or along a line of impulse more or less regular, and the crests of the earthquake waves of every order of which we are about to speak, or, as they may be called, the *earthquake cotidal lines*, will, in their progress of propagation through the earth and sea, alter their curvilinear forms, by changes in their respective velocities, becoming more and more distorted from the original form; but, in every case, these cotidal lines will form closed figures. This will be evidenced to the eye by reference to our diagram of earthquake cotidal lines, (see Plate I.), the theory of which will be further explained hereafter.

This is but a very incomplete sketch, however, of what takes place; for, besides the wave analogous to a tidal wave produced and propagated on the surface of the ocean, a second wave (of sound namely) will be propagated through the mass of the ocean water likewise, with a velocity far greater than the former, and will reach the land, and be heard there as a sound long before the great surface wave will have rolled in. The terrestrial sound wave is isochronous with the great elastic wave or earth wave of shock.

Referring to the internal mechanism of a fluid wave, as experimentally observed by the Webers,* (see Plate II. Fig. 1), it is not yet known that precisely analogous motions take place amongst the particles of solids within their limits of elasticity, when transmitting a wave of the first order; but it seems highly probably that there is a close analogy in the motions of the particles in both cases, so that the particles of a table land of solid rock, transmitting an elastic wave, or earthquake shock, from a distant primary impulse, do, in all probability, describe similar elliptic curves to those of a watery wave, and varying in the same way with respect to depth, though much smaller, because withheld within the elastic limits due to the particular rocky mass or masses, and transmitted also with inconceivably greater velocity. This, however, is certain, that the *surface* of the solid earth does undulate; it has been repeatedly observed to do so. The *transit* of the wave along the surface, even, has been observed, as in the great earthquake of Jamaica, in 1692: hence, it is certain that any particle upon the surface of the earth, under such circumstances, must describe either a circle or an ellipse, most probably the latter, whether those within the mass of the undulating land do so or not.

Difficult as it may seem at first to reconcile to our common notions of solid bodies, that such internal motions should pass through them, causing compression or even intermobility of their particles within their elastic limits, yet, through large measurable spaces, and with immense velocity, such motions are, in fact, before us constantly: the vibrations of the air of a drawing-room shake the solid walls of the house, when a tune is played upon a piano-forte, or otherwise the tune could not be heard in an adjoining house. Captain Kater found that he could not perform his experiments upon the length of the second's pendulum any

* Wellenlehre, auf experimente gedründet.

where in London, for that the solid ground every where vibrated by the rolling of carriages, &c.

Captain Denman, R. N., found by experiment that the vibration of the ground, produced by the passage of an ordinary goods train upon a railway, extended laterally more than eleven hundred feet from the line, in marshy ground, over sandstone. He also discovered (what is very interesting as respects our question) that the vibration only extended about one hundred feet vertically, when tried *above* a tunnel in sandstone rock. Houses and towers rock with the wind; Salisbury spire moves to and fro in a gale more than three inches from a plumb line. Tall chimney stalks of manufactories, when first built, will vibrate four or five inches, by a man merely rocking himself backwards and forwards upon the top, and various other instances might be cited. In all these cases, however great the aggregate motion of the whole vibrating body, there is no breach of continuity of its particles while ever they oscillate within its specific elastic limits.

In the collieries of the thick seam coal in the north of England the fire clay and sandstone roof is supported by temporary props of timber during the cutting out of the pillars of coal, and finally these props are withdrawn when large areas have been wholly exhausted of coal. The roof is then suffered to drop down, and the whole supereminent mass, up to the surface, often consisting of a thousand feet in depth of strata of shale, sandstone, coal, &c., becomes fractured, breaks down, and subsides upon the floor of the former coal seam. The fracture and subsidation of these colossal masses is not only attended with the most awful noises underground and at the surface, but with shocks felt in the neighbourhood, which precisely resemble earthquake shocks, though less violent. A powerful blow produces quite similar effects upon the solid mass of the earth. At the latter end of last century, one or more of the great vertical and impost stones of Stonehenge suddenly fell down: the concussion produced a wave, which was transmitted around in every direction, like that upon a pool of water into which a pebble has been dropped, and the shock felt in all the neighbouring hamlets was so great that for some time, until the cause was discovered, it was thought to have been an earthquake, as in fact it was, though not produced by natural causes. So also when the great Spanish powder magazine, said to have contained 1500 barrels, was blown up, near Corunna, at the conclusion of Sir John Moore's retreat, I

have been told by officers who were present that the ground rocked sensibly for miles away, and the wave was felt at a distance before the sound of the explosion was heard.

We are now in a position to return and explain why a body displaced, as the stones of the Calabrian obelisks, is not replaced, in an earthquake.

The centre of gravity of the stone, and therefore the stone itself, in accordance with the principles we have laid down, describes an ellipse in space, and, from the specific elasticity of almost all rocky solids, forming the earth's crust, this will be an ellipse of great eccentricity; the horizontal major axis may be, perhaps, a few feet; the minor vertical axis is but a few inches, or the fraction of an inch, because the form of the wave is very low and flat, its amplitude great, and its velocity immense. Now the horizontal velocity of the centre of gravity will be greatest at the top and bottom of the ellipse; but when approaching the top, the inertia of the mass assists in holding it fast to its bed; while on the back stroke, or when the centre of gravity is returning to the bottom of the ellipse, the inertia of the mass acts in freeing it from the friction or adhesion of its bed, and the mass readily becomes shifted upon it. Thus the conjoint effect of the upward, downward, and horizontal motion of the mass, combined with its inertia, is such that it is not moved from its bed by the forward motion of the wave, but is left behind, as it were, by its backward motion, that is, it is finally left, having been moved in the direction of translation of the wave. It is possible that some movement *may* take place occasionally by the forward stroke, but it can rarely occur that the conditions of equilibrium of the body after displacement, and the force, direction, &c., of the subsequent back stroke, are such as just to undo what the forward stroke or shock had done in way of disturbance.*

But it is stated that occasionally bodies are thrown down in opposite directions, for instance, walls standing north and south are prostrated both to the east and to the west. This and many other accidental anomalies, of course, will occur, but do not affect the truth of the general view. Thus a mass of masonry may be so conditioned as to height, weight, and connexion of parts, as to offer more resistance to the forward than to the back stroke, or *vice versa*, or may be shattered by the one and thrown down by the other.

* The singular inversion of the pavements of towns by the Calabrian earthquake is also thus explained.—See Lyell, vol. i. p. 488, 2nd edit.

But another solution is possible for such cases of prostration in opposite directions. When the *earth wave*, as we may call the shock, comes from seaward, and travels through a mass of stratified rock, or of diluvial matter, or other material of low elasticity, towards an inland range of mountains, consisting of masses of hard, crystalline, and highly elastic rocks, part of the wave will pass on, and a slight earthquake will be felt throughout the mountain range; but a portion of the wave will be reflected, and will return back, and pass a second time through the country first agitated, but now in an opposite direction; and thus walls, or other such masses, which remained standing from the primary earth-wave, may be prostrated by the secondary or reflected wave, and in the contrary direction to those first thrown down.

I proceed now to explain, in accordance with my theory, the circumstances of *the great sea wave* and of *the aerial sound wave*, attending most great earthquakes.

Michell rightly attributes the origin of the great sea wave to the primary disturbance of the ocean water, directly over the centre of disturbance, propagated in every direction, like the circles upon a pond when a pebble is dropped into it; but he does not give any satisfactory account of why it is that this wave succeeds the earth-wave or shock by a long interval; indeed the theory of wave-motion was then in too backward a state to have enabled him to do so. Recent authors have not been even as near the truth as he was when he attributed the different rates at which the great sea wave moves towards several distant surrounding shores, to its true cause, namely, the variable depth of the water.

Thus Darwin says:* "In almost every severe earthquake the neighbouring waters of the sea are said to have been greatly agitated. The disturbance seems generally, as in the case of Conception, to have been of two kinds, first, at the instant of the shock the water swells high up on the beach, with a gentle motion, and then as quickly retires; secondly, some time afterwards the whole body of the sea retires from the coast, and then returns in waves of overwhelming force. The first movement seems to be an immediate consequence of the earthquake affecting differently a fluid and a solid, so that their respective levels are slightly deranged; but the second case is a far more important phenomenon."

* Voyage of a Naturalist, p. 309.

"During most great earthquakes, and especially in those on the west coast of America, it is certain that the first great movement of the waters has been a retirement. Some authors have attempted to explain this by assuming that the water retains its level while the land oscillates upwards; but surely the waters close to the land, even of a rather steep coast, would partake of the motion of the bottom. Moreover, as urged by Mr. Lyell, similar movements of the sea have occurred at islands far distant from the chief line of disturbance, as was the case with Juan Fernandez during this (Conception) earthquake, and with Madeira during the famous Lisbon shock. I suspect," he says "(but the subject is a very obscure one), that a wave, however produced, first draws the water from the shore, on which it is advancing to break. It is remarkable that while Talcahuano and Callao (near Lima), both situated at the head of large shallow bays, have suffered severely during every earthquake from great waves, Valparaiso, seated close to the edge of profoundly deep water, has never been overwhelmed, though so often shaken by the severest shocks. From the great wave not immediately following the earthquake, but sometimes even after the interval of half an hour, and from distant islands being affected similarly with the coast, near tbe focus of the disturbance, it appears that the wave first rises in the offing, and as this is of general occurrence, the cause must be general: I suspect we must look to the line where the less disturbed waters of the deep ocean join the water nearer the coast which has partaken of the movement of the land, as the place where the great wave is first generated. It would also appear that the wave is larger or smaller according to the extent of shoal water that has been agitated, together with the bottom on which it rested."

Darwin fails in giving any explanation of the phenomena, in fact he does not pretend to offer any.

Michell, upon this point (and it is one of the most important and fruitful facts in the whole range of earthquake phenomena) is totally astray; he attributes the retreat of the water from the shore, previous to the advance of the great wave, to a distant subsidence somewhere in the bottom of the sea, from the sudden giving way of some cavity, in consequence of a vacuum produced by the condensation of steam; or he supposes that the whole mass of the land may be suddenly elevated by pent-up steam beneath it, and let down again upon its escape, and

that thus the retreat of the water is only apparent, and due in reality to the previous rise of the land.*

It is scarcely necessary to refute these hypotheses at length: as to the first, granting such a cavity under the deep sea to be suddenly filled, it would produce no immediate sensible effect on the distant shores, and if it ever produced any, it would be a swell rolling in subsequently, and not a recession at the moment of shock.

The second hypothesis is one of those samples of geology run wild, by which if only a sufficiently monstrous postulate be granted, anything may be accounted for.

Nor, lastly, is the reviewer of Lyell in the Quarterly Review, No. lxxxvi. p. 459, more fortunate in his explication. He says: "If a portion of the bed of the sea be suddenly upheaved, the first effect will be to raise over the elevated part a body of water, the momentum of which will carry it much above the level it will afterwards assume, causing a draft or receding of the water from the neighbouring coasts, followed immediately by the return of the displaced water, which will also be impelled by its momentum much further and higher on the coast than its former level."

This last view rests upon a mistaken notion of the mechanical conditions of the question. There is not the smallest evidence, that a wave produced far away at sea over a centre of disturbance, would produce any withdrawal of water *at the instant* from shores often distant by hundreds of miles, and, moreover, this theory allows no time for the earth wave or shock itself, produced under such conditions, to reach the land, which it is observed to do, at the instant of the recession of the water.

Mr. Lyell himself offers no solution, nor have I been able to find one elsewhere; I believe, therefore, that the explanation I am now about to give, for the first time, renders a true account of the phenomena, and, like all truth, when once grasped, will be found fertile in shewing the way to further and more advanced knowledge.

First, then, in almost all great earthquakes it is admitted the shock comes from the sea. Let us assume a centre of disturbance far from land, below the

* Michell's Phil. Trans., vol. li. p. 614.

bed of the deep ocean; let it be a submarine eruption of actual lava poured out, a sudden breaking through of the earth's crust and injection below with lava, or any other disturbance, it matters not what, sufficiently sudden, violent, and extensive to produce an earthquake. The impulse at this centre will spread itself in all directions, but for simplicity we will limit our consideration to what will take place as respects a single distant land within range of the earthquake.

The original impulse given to the bed of the sea acts simultaneously upon the earth, the sea, and the atmosphere, originating at the same instant, and transmitting one or more waves through each.

The earth wave moves with an immense velocity, probably not less than 10,000 feet per second, in hard stratified rock, and perhaps little short of this in the less dense strata.

Dolomieu says of the Calabrian shocks: "They were as sudden as the blowing up of a mine."

It will be proper here to give some proof of the actual *progressive* motion of the earth wave or shock; that each portion of the disturbed country is shaken *in succession* by the progress of the earth wave, and not the whole at once, as very commonly believed. Thus Spallanzani, in his Travels in the two Sicilies, in recording the facts observed by him of the earthquake at Messina (part of the great Calabrian earthquake), says: "A very violent noise, like the rolling of carriages, was first heard at Messina, while a thick cloud (of dust) rose from the shore of Calabria opposite, where was the centre of the earthquake, the propagation of which was apparent by the successive falls of buildings from the point of the Faro to the city of Messina, as if, at the former point, a mine had been sprung, which extended along the shore, and continued into the city."

It is needless to multiply such facts, which occur abundantly in earthquake narratives, to prove that the earth wave passes parallel to itself in succession through the shaken country. I shall shew hereafter, however, in speaking of *systems of vibrations*, that, under particular conditions as to geological formation, the whole mass of a country may be shaken at one and the same instant.

The earth wave, or shock, reaches the devoted land at the same instant that the sound of the crash and thunder of the submarine war of elements reaches the ears of its inhabitants, for the wave is itself the bearer of the sounds first transmitted

through the solid earth. These are so far exactly the phenomena observed: the shock is felt, and the rolling sounds are heard at the same instant, or as nearly so as can be told. It may, however, occasionally happen that the rolling sounds shall precede considerably the actual shock, because the amount and peculiar character of the disturbance at the centre of impulse may be such as, by several partial disturbances, to set in motion waves of sound through the earth or sea, before any sufficient impulse has been given to propagate a sensible shock; and further, as the velocity of the sound wave through the earth will probably be from 7000 to 10,000 feet per second, or even more, while the velocity of the sound wave through the sea will be about 4700 (both in round numbers), so it will generally occur that the sound will be heard accompanying the shock, as transmitted by the former medium, and still the same sound be heard some time after the shock, thus transmitted more slowly through the latter medium, viz., the sea.

Occasionally waves of sound may be wholly wanting, owing to *no fractures* taking place in the earth's crust; the elastic earth wave, or shock, in such cases, being due merely to compression produced by sudden *flexure.*

So also, if the centre of impulse lie deep in hard, elastic primary rock, extending beneath a country consisting superficially of soft rock, or of diluvial matter of very low elasticity, the sound wave will reach the ear at a very distant point of the surface, by passing horizontally through the elastic rock below, and then vertically through the small distance to the surface occupied by the softer and less elastic materials, thus reaching the ear by a quicker channel than if it passed first vertically up from the deep seat of disturbance, and then passed horizontally through the superficial deposits; but the latter course is that which the great earth wave or shock *must* take to be felt horizontally at the surface; hence, the sound must be heard, in such circumstances, before the shock; and while the sound, occasionally accompanied by a slight vertical shock, will appear to come up directly from under the feet of the hearers, the principal shock will be felt laterally as coming from a distance—a fact actually recorded by Dolomieu in his Dissertation on the Calabrian Earthquake of 1783, where, on the granite mountains, the sound was heard before the shock was felt; but in the great diluvial plain the shock was felt before the sound was heard.

In similar conditions, the great earth wave itself may, when transmitted from profound depths, be diverted by difference as to elasticity of formation, from

its direct course, and, passing horizontally through deep, elastic strata, may reach the surface vertically at distant points, and produce those shocks upwards, from directly below, sometimes spoken of in earthquake narratives.

Again, if the seat of disturbance be at a great depth, the earth wave must reach the surface in its immediate neighbourhood in vertical and diagonal lines of undulation, and produce similar effects as to shock as those last spoken of. This is the case with shaken countries close to volcanoes, where the seat of impulse is often close underneath.*

The earth wave which reaches the shore (from an origin beneath the sea) is a real undulation of the surface: it is a wave, whose magnitude depends upon the elasticity of the crust of the earth which has received the original impulse, and upon the nature and force of that impulse; whose vertical height appears to vary from a fraction of an inch to several feet; generally, its vertical height seems to be from two to three feet in great earthquakes, and its length variable, according to the depth and elasticity of the strata which it affects.

Now, at the moment of its origin, the earth wave is vertically below the great sea wave, which is raised by the initial impulse upon the surface of the ocean; both move landwards together, but the earth wave rapidly outstrips the sea wave, because, while the velocity of the former depends upon a function of the elasticity of the crust of the earth, the velocity of the sea wave, depends upon a function of the depth of the sea (see Plate II. Figs. 2, 3, D.). Leaving, therefore, for the present, the sea wave in its progress towards the land, we will follow the earth wave in its silent and rapid transit beneath the deep ocean, and trace what takes place when it gets into soundings, and at last reaches the devoted shore.

While passing under the deep water of the ocean it gives no trace of its progress at the surface, in all probability; but, as it arrives in soundings, and gets into water more and more shallow, the undulation of the bottom, the crest of the long, flat-shaped earth wave, brings along with it—carries upon its back, as it were,—a corresponding aqueous undulation, slight, long, and flat, upon the surface of the water. This, which, adopting Airy's nomenclature, might be called the "*forced sea wave*" of earthquakes, has no proper motion of its own; it is simply a long, low ridge of water, pushed up at the surface by the partial elevation of the bottom

* See Professor Ferrara's Account of the Earthquake at Catania in 1833, Silliman's Journal, vol. ix. p. 216.

immediately below it, this latter elevation travelling with such immense velocity, that the hillock of water pushed up above it has not time to flow away laterally, and reassume its own level.

Thus, then, the earth wave below, when in shallow water, is attended by a small *forced sea wave*, vertically over it, upon the surface of the sea, and these two reach the inclined beach or shore at the same moment; but as the beach is so inclined, and the forced sea wave, as well as the earth wave, are long and flat, and the velocity of the latter very great, the earth wave, as it were, slips from under the forced sea wave, at the moment of reaching the beach, which it for the moment elevates, by a vertical height equal to its own, and as instantly lets drop again to its former level. (See Plate II. Fig. 4, and M.)

There is thus an *apparent* small recession of the sea from the shore, at the moment of the shock, followed almost directly by its flowing up something higher than the usual tide-mark, as the forced sea wave now breaks, and expends itself upon the shore. It is this forced sea wave, also, that communicates the earthquake shock to ships at sea, as if they had struck upon a rock. When, however, a ship is so struck in very deep water, as in the case of the Winchelsea, on the passage home from Bengal, in latitude 52° N., longitude 85° 33′ E., hundreds of miles from land, we may conclude that the centre of disturbance is either directly under the ship, or very near, and that the shock felt is the actual earth wave shock, transmitted vertically or diagonally upwards, like a blow, through the deep water.*

It is possible that the aqueous sound wave may communicate a vibratory jar to a ship afloat in the water through which it passes, but not the shock universally described as like striking on a rock, and often mentioned as violently straining the timbers of the ship.†

This, I believe, is the true explanation of the small apparent recession of the sea, just at the moment of the shock; and combinations analogous to this will account fully for all the strange movements of distant lakes, islands, rivers, &c. &c., recorded as occurring during great earthquakes. The earth wave, for instance, of the Lisbon earthquake, when it had reached Scotland, and passed under the Highland lakes, must have produced similar phenomena of oscillation in the waters on their shores; and in passing under the bed of a river, in

* Quarterly Journal, vol. xvi. p. 184.

† Ibid. vol. xvii. p. 43.

the direction contrary to its course, must, in various places, have produced the effect of the retardation, stoppage, or reflux of the current for a few moments, as in the case of the South Carolina earthquake of 1811, where the course of the Mississippi was temporarily arrested below New Madrid;* or, as in the great Calabrian earthquake, where the courses of many rivers were arrested at the moment of the passage of the first shock, the waters drying up all at once, as the ridge of the earth wave dammed them up above, and caused their waters to run proportionately rapidly off, down stream, behind the earth wave. They almost immediately began to run again as usual, but with increased volume, owing to the short withholding of their waters. This phenomenon was particularly remarked in the river Metramo, at the bridge of Rofarno.

Dolomieu, in his Dissertation on the great Earthquake in Calabria Ultra of 1783 (a scarce work, of which a limited number of copies were printed at Rome, in 1784), records the above, and several other remarkable facts ascertained personally by him, none of which have hitherto been explained, but of which I now propose explanations accordant with my general theory.

The great Calabrian plane consists of a vast, deep, diluvial deposit, reposing upon the hard granite and slates which form the mountain chain of the Appennines in that country. These plains, which have a gentle slope seaward, are cut into deep ravines and valleys, of greater or less magnitude, in all directions, by the excavations of the rivers and drainage of high and plain lands, so that the vast mass of loose material composing the latter is, to a certain considerable depth, divided, as it were, into a number of small, insulated table lands, by intervening glens with steep escarpments.

Dolomieu compares it to a number of cubes, or rather of irregular flat masses of damp sand, placed near each other upon a flat table; and he describes the general effect of the earthquake as like that which would be produced upon these disconnected masses, by shaking the table with a horizontal motion, namely, a general tendency to level the whole—to break down the escarpments of the valleys, and fill them. Hence, the most capricious changes of the face of the country resulted from the earthquake: valleys were dammed across in a moment by the "slipping" of vast masses of their loose escarpments, often bearing upon them still rooted woods, vineyards, and olive yards, and even houses.

* Lyell, vol. i. p. 470.

The streams, whose beds were in the bottoms of the valleys, now quickly formed lakes above these dams, and their final overflow often traced out new river courses over the table land, or changed the whole aspect of the valleys below by violent "debacles" consequent upon their giving way. I notice these, and refer to Dolomieu's Dissertation for many other singular details, in order to remark that those and all similar phenomena do not properly constitute part of the earthquake at all; and, in order to form clear notions of earthquake mechanics, we must carefully distinguish between these, which are but *consequences of the consequences* of the earthquake, and the earthquake wave itself, which gives rise to them all. The earth wave shakes the country; the features of its surface are altered by the filling of valleys and levelling of eminences; a new state of things is instantly brought about, as regards its drainage, and all its meteorological circumstances alter in proportion. Hence, when, in the loose narratives of earthquakes, which abound with ill-made observations, fanciful and figurative language, and exaggeration, we read of "lakes suddenly appearing where all was dry before," rivers and lakes "bursting up out of the earth," "lightnings and clouds of smoke or dust accompanying the shock," we must bear in mind that these are mere accidents, contingent upon the consequences of the principal phenomenon, the transit of the earth wave, namely, upon the disturbance of the surface of the land *reacting* upon its drainage, and producing violent electrical disturbances by friction, by pressure, by changes of temperature, and these all again reacting upon its climate, so as often permanently to affect it.

Hence, to arrive at a true theory of earthquake mechanics, it is not required that we should be able to predict, or even to explain, all of these *doubly secondary* contingent circumstances, the conditions of which must be, for the most part, so local as to forbid the attempt. Many, however, of such contingent phenomena, where we have the conditions sufficiently given, can be explained by direct reference to our theory.

For instance, Dolomieu records of Calabria, and the same statement is made of other earthquakes, that, "at the moment of the shock, several springs spouted up their water like fountains." The sources of copious springs usually lie in flat plates or fissures filled with water, whether issuing from solid rock, or from loose materials: now, if a vein, or thin, flat cavity, filled with water, be in such a position that the plane of the plate of water or fissure be transverse to

the line of transit of the earth wave, the effect of the arrival of the earth wave at the watery fissure will be, at the instant, to compress its walls more or less together, and so squeeze out the water, which will, for a moment, gush up at the spring head, like a fountain, and again remain in repose after the transit of the wave. The inertia of the fluid will aid this effect at the instant of transit of the rearward slope of the wave over the spring, that is to say, at the moment that the ridge of the wave sinks again, on passing over the spring, the water will appear to rise.* To this many other such curious, minute, accidental earthquake consequences might be added and explained, but it would be a tedious and useless labour, as the explanations of all such will be apparent easily to those acquainted with physics, where the conditions have been properly observed.

Before leaving the subject of the great earth wave, however, it is necessary to make some observations as to the change which will take place (under certain circumstances of geological formation) in the transit of the wave, by which, in place of its progressive motion, the whole country will move, or be more or less completely shaken at the same instant of time, so as, in fact, to produce one simultaneous shock over a larger or smaller space at the same instant.

Where a wave of elastic compression, such as our earth wave, passes through a body, varying, in specific elasticity, in several parts of its course, or passes from one body to another of different elasticity, at each such change of medium the wave changes its velocity, and in part changes its course, a portion being reflected and a portion refracted, analogous to a wave of light, in passing through media of variable density or of different refractive indices; so also, if the wave passes from a highly elastic body to one of very low elasticity, and again into a third body of high elasticity, in proportion as the wave continues unbroken, the bodies must have a common time of vibration or of wave transit, at the surfaces of contact. A popular illustration of these truths is afforded by a glass of sparkling champagne, which will not ring clear when the glass is struck, while the foam continues to crown the liquor, but no sooner has its disappearance enabled the glass and the wine to vibrate, as a system, than the tone becomes musical.

* Fluids and all loose bodies may also be thrown upwards, when the direction of wave transit is vertical or nearly so.

To apply this to our subject: when the earth wave passes abruptly from a formation of high elasticity to one of low elasticity, or *vice versâ*, it will be partly reflected; a wave will be sent back again, producing a shock in the opposite direction; it will be partly refracted, that is to say, its course onwards will be changed, and shocks will be felt upwards and downwards, and to the right and left of the original line of transit of the wave. This is exactly what has been observed to take place. Thus, Dolomieu informs us that, in Calabria, the shocks were felt most formidably, and did most mischief, at the line of junction of the deep diluvial plains with the slates and granite of the mountains, and were felt more in the former than in the hard granite of the latter. Houses were thrown down in all directions along the junction, and fewest of any where these were situated in the mount ains.*

Here the transit of the wave was from the clay and gravel, which have the lowest possible elasticity, into the granite, whose elasticity is remarkably high; and hence the shock, after doing great damage by varying its direction, and returning upon itself, at the junction, was at once eased when it got into the elastic material of the mountains. But if the case be converse, if the earth wave pass from highly elastic rock into a mass of clay or sand (suppose lying in a small-sized valley), and pass across this into similar elastic rock at the opposite side, all the former results will follow; but, in addition, the whole mass of clay, or sand and gravel, in the basin of the valley, will be shaken as a whole by any powerful shock, which will be felt over its whole area at the same instant; in other words, the contents of the basin or valley will be constrained to vibrate as one system, with its walls, namely, the elastic rock of its sides. This gives the solution of the fact frequently recorded of places so circumstanced, and at not very great distances, feeling the shock of the one earthquake at the one moment.

We have thus traced many of the variable and secondary effects of the transit of the great earth wave, and may remark, in concluding this branch of our subject, that earthquakes must be regarded neither as the cause nor as the immediate effects of the elevation of a district of the earth's surface, but merely as the remote effects of elevations occurring at a remote centre, so that the true definition of an earthquake is, *the transit of a wave of elastic compression in any*

* See also M. Place's Account of the Earthquake in Chili, 1822, Quarterly Journal, vol. xvii. p. 42.

direction, from vertically upwards, to horizontally, in any azimuth, through the surface and crust of the earth, from any centre of impulse, or from more than one, and which may be attended with tidal and sound waves dependent upon the former, and upon circumstances of position as to sea and land.

Our knowledge is not at present sufficiently advanced as to the laws of large waves of elasticity passing through solids, to be able to do more than rudely to predict the many strange alterations of the original wave which will be produced by particular local circumstances, such as by its passing from low to high land, from hard to soft rock, or *vice versâ*, round great axes of hard rock, and round great bodies of inland waters, or through masses of softer rock, reposing on much harder, and suddenly reduced as to depth, in which case a single shock will probably be divided into two or three in quick succession, and varying in direction.

I return, therefore, now to the *great sea wave*, which, after having been elevated at the same origin and instant of time with the earth wave, we left pursuing its course to land, over the deep ocean. While over the profound depth of the ocean, its course, though greatly slower than that of the earth wave, will still be exceedingly rapid; and, like all deep sea tidal waves, it will have an equal slope before and behind; its amplitude will be very great, and its slope so gentle, that it might even pass under a ship without being noticed. It is here, but a long, low swell, of enormous volume, and with an unbroken surface; so it continues until it reaches the "edge of soundings," and here a new phenomenon is manifested. It is capable of proof theoretically, and the fact is daily observable in tidal estuaries or rivers, that when the tidal wave (such a wave as we are here considering) leaves the open sea, its front and rear slopes being equal in length and similar in form, and advances into the shallow water of an estuary or near the shore, its front slope becomes short and steep, and its rear slope long and gentle; advancing still further, the rear slope becomes more and more flattened about the middle of its length, then becomes depressed at this point, and as the wave continues to advance this depression deepens, and at last the wave becomes broken into two or more smaller waves (see Plate II., figs. 5, 3, and 7); and when the depth of water below its mean surface becomes less than the altitude of these waves, they will lose their equilibrium, become broken, and topple over, falling in "breakers" upon the shore. It is unnecessary here to enter more fully

into the conditions of this peculiarity of tide waves; enough has been stated to show that a single shock, or earth wave, may be succeeded either, first, by one great sea wave, rolling in long after the shock has passed, if there be deep water close into the shore, in which case the wave will come in as a long and wide, but low and unbroken swell, and may do little or no damage, which fully explains Darwin's case of Valparaiso, as above quoted.* In this case, if more than one great sea wave arrive to land, there must have been more than one earth wave; in fact, there will be one sea wave for every earth wave or shock, but the intervals between the shocks may be such, or the primary impulses so circumstanced, that two or more such waves may arrive at the land together, or so nearly coincident as to appear as one; and as there is deep water close in shore, and, therefore, no beach, the apparent recession of the sea, at the moment of the shock, will not take place; but instead, there will be a small elevation of the sea, or forced sea wave, close in shore, at the moment that each shock reaches the land, the height of which will be approximately the same as that of the earth wave itself, and may, in fact, become a rude measure of the amount of vertical movement of the earth at the crest of the earth wave.

But further, the interval of time between two shocks, or, what is the same, between two forced sea waves (which we must recollect always keep company with the earth waves), may be such, that the forced wave of a succeeding shock shall coincide at the shore with the great sea wave due to a preceding one, and thus the forced wave be obliterated, or accumulated into the great sea wave; and this may happen upon certain points of an indented shore, and not on others: or it may happen upon certain points of a perfectly straight shore, with deep water all along, and not on others, provided the geological formations at different points along the coast, and under the surrounding sea, differ in density and elasticity, so that the time of the earth wave transit is greater in one formation than in another; in this case, the shock will arrive a very little later upon one part of the coast than upon the other, and the forced sea wave along with it, as may be made more evident to the eye by a geological map of earthquake cotidal lines. (Plate I.)

From the principles already explained, a single earth wave or shock will,

* Page 66.

where the sea is shallow and the shore shelving, be at first attended by one great sea wave, which, on coming within soundings, may divide into several, according to the height of the original wave and the depth of the water; these secondary waves shall arrive in succession upon the land, and each earth wave will be followed by a similar sequel of divided sea waves; or, if the depth of water close into the shore be sufficient, in proportion to the height of the original wave, although the latter be shelving or beached, it may come in singly, and only altered from its form when passing over the deep ocean, by having become steep and impending on its front slope until it breaks upon the land.* Thus, then, we have a complete account rendered of all the apparently perplexed facts recorded in the narratives of earthquakes, as to the occurrence sometimes of a number of shocks, and but one great wave; sometimes of many shocks and several great waves; and sometimes of fewer great waves than shocks.

It may be here remarked, that although the earth wave and the great sea wave have a common origin, and set out with motion in the same direction, that it by *no means follows that they shall both arrive at land with precisely the same direction of motion;* for inspection of the map of cotidal earthquake lines (see plate I., and Explanation of the Plates) will shew that, as the earth wave cotidal lines become distorted by change of strata, or of geological formation, so the great sea wave cotidal lines become distorted by change in the depth of water, and hence, may intersect at one or at several points; and thus the shock of an earthquake may appear to come from one direction, while the great wave may roll in apparently from a different one, although they both started from one point, and at the one moment, which again explains some of the most perplexing accounts given in earthquake narratives.

Just before the great sea wave comes in, the sea will largely and rapidly retire from the shore. Again, after the primary great sea wave has come on shore, the sea will, upon its retreat, fall back far beyond its usual limits; and again returning, a second wave may follow the first, of less size; and again, a third or a fourth, until these *waves of oscillation* have spent themselves. The possibility and extent of this phenomenon depend upon the form and slope of the beach, or shape of the bottom of the shallow water close in shore. This was

* See Caldcleugh's Account of the Earthquake at Conception, in 1835, Phil. Trans., where the wave was twenty-eight feet high.

exactly what occurred after the earthquake at Callao, in South America, in the year 1747, as related by Ulloa in his Voyages.*

That the whole mass of the land over vast areas is often permanently elevated more or less, and to variable amounts at different points, during earthquakes agitating these same areas, is proved beyond doubt; it therefore must be held in view that all the above phenomena of wave motion, in both earth and sea, are liable to perturbations, and to become complicated, by movements of permanent elevation or depression in the land, general or partial, and the effects of which, it may be often difficult or impossible subsequently to separate; but the distinction is ever to be held in mind between those elevating forces, which have a common origin with the earthquake, and which permanently affect the level of the disturbed country, and these impulses, the transient effects of which, acting at remote distances, constitute the earthquake properly so called.

It seems probable that the earth wave, in passing through a country already shattered, or consisting of a variety of heterogeneous formations, and with a very uneven surface, may become broken or separated, in the way already explained, into a succession of smaller shocks or earth waves, and as the amplitude or length of these waves is small, while their velocity is still very great, they may break up the mass of the rock or ground through which they pass, by the amount of internal motion exceeding the elastic limits of the formation, and thus give rise to fissures which, in hard material, may rapidly open and close, as the succession of partial earth waves passes through. This explains the phenomena recorded as happening in the great earthquake of Jamaica of 1692, where the fissures opened and closed, in vast numbers at a time, with such rapidity, as not only to swallow human beings, but even to bite them in two, when in the act of falling in.†

The casting out of water, mud, &c., from such fissures, seems to be merely an accident due to these fluids having found their way from lakes, rivers, &c., into the newly formed fissures when open, and being squeezed out again when they closed, or thrown out by inertia on the transit of the wave, as already explained in the case of springs.

* See Caldcleugh, Phil. Trans., Earthquake at Conception, of 1835; and for a collected account of the coming in of great sea waves, Woodbine Parish, in Phil. Magazine for 1836, vol. viii. page 181.

† Lyell, vol. i. p. 512.

Lyell's explanation of the alternate opening and closing of fissures, namely, that "we must suppose the earth was by turns heaved up, and then let fall again,"* seems erroneous and unsupported by observation; no amount of elevation, transitory or permanent, recorded in even the most violent earthquakes, would be sufficient to account, in this way, for the opening and closing of fissures of a few inches in width, much less of several feet, as repeatedly observed.

As it has been before remarked, that the cotidal lines of the earth wave become distorted by passing through heterogeneous masses, so, in passing through a broken country of variable formation, two partial earth waves, separated from the original wave, may cross each other, and produce a larger wave at this nodal point, and in this case we shall have fissures, also intersecting or radiating in various directions from the centre of the node, like cracks in a broken pane of glass, which is the explanation I would give of this phenomenon, as observed in the great Calabrian earthquake of 1783, at Jerocarne.† It is exceedingly improbable that radiating fissures, so produced, should ever all close again after the transit of the wave, as many of the cuneiform masses between them must become greatly displaced; their remaining open partially is, therefore, no proof of permanent elevation, as Mr. Lyell supposes.

On the other hand, it may occur that the earth wave, in passing from heterogeneous formations of low elasticity, into one vast and deep homogeneous formation, as, for instance, of crystallized igneous rocks, possessing a high elasticity, will be largely increased in amplitude, and thus may (like the great sea wave over the deep ocean) pass through such a country, with its immense velocity unabated, and yet, from its small altitude, and great amplitude, or, in other words, from the great breadth and flatness of the wave, it may do no mischief, nor even be noticed, except in the slight agitation it may produce in lakes or other inland waters.

This appears to have been the fact with the great Lisbon shock, on reaching the crystallized primary or igneous rocks of Scotland, where its passage was only known by the disturbance of the waters of the Highland lakes.

At Loch Lomond the water, without any apparent cause, rose against its banks, and then subsided below its usual level: the greatest height of the swell

* Lyell, vol. i. p. 483.

† Ibid. p. 507.

was two feet four inches.* In this instance, it seems most probable that the amplitude of the earth wave was so great, that the entire cavity or basin of the lake was, as it were, nearly at the same instant, tilted or canted up, first at one side, and then at the other, by the passage of the wave beneath it, so as to disturb the level of the contained waters by a few inches, just as one would cant up a bowl of water at one side by the hand; in such a case, the height of the original terrestrial disturbance would be much less than that of the subsequent swell, or oscillation of the water, produced by it, so that the earth wave itself, upon land, might be quite imperceptible to the senses directly.

It is even possible that, when the earth wave originates at profound depths in the earth's crust, it may be propagated through masses of rock of similarly high elasticity to various remote regions, and either escape altogether, or be very little felt in closely adjacent regions, whose formations are of soft, stratified rocks, of low and variable elasticity, reposing upon the more elastic primary rock below; so, also, the earth wave will pass with *unequal velocities, in different directions*, in stratified, laminated, or pseudo-crystalline formations, such as various sands or limestones, roofing slate, &c. Thus, an earthquake shock originating at or near Lisbon, might be felt in the older rocks of Scotland or of Wales, and yet not be observed, or be much less observable, in England, although it should have equally passed under the latter country. This appears actually to have been the case, in the great Lisbon earthquake.†

So, also, the earth wave or shock propagated in all directions at once, from the centre of impulse, if this be situated, with formations of low elasticity at one side of it, and those of high elasticity at the other, may reach very distant regions by transit through the latter, while it may be scarcely felt in closely adjacent ones situated upon the former.

Again, if two earth waves or shocks be propagated through a region towards a line, where, by change of formations, partial reflection of the wave takes place, as already explained‡, the recurrent wave of the preceding shock, may meet the advancing wave of a succeeding one, and a *nodal line of earth wave* shall result, so that along one particular stripe of country, at right angles to the line of transit of the shock, or nearly so, the destruction shall be far greater produced by the accumulated wave than at any one line in advance of it or behind it, and yet there

* Lyell, vol. i. p. 507. † Phil. Trans. 1760. ‡ Page 26.

shall be no reason discernible for all this, in the form, structure, or circumstances of the country itself where so shattered.

And again, if, by the crossing of two partial earth waves, the crest of one wave fall into the hollow of the other, a *negative node* will be produced at their intersection, so that the ground here shall not be moved, though in the midst of a country shattered all round it. Facts have been occasionally observed, that scarcely admit of any other explanation. Thus, Dolomieu states that, in the centre of Radicina, a small village totally levelled by the Calabrian earthquake, one solitary small house remained, without a sign of having been disturbed. But it would be tedious to follow further such corollaries from our general principle, many of which will occur to those familiar with the mechanics of waves.

Having thus traced most of the direct and collateral phenomena resulting from the transit of the earth wave, and of the great sea wave, it remains to say a few words as to *the aerial wave*, that is to say, *the sound* of the original disturbing impulse, transmitted from this point to or over the land, *through the air*.

The wave of sound in air, has a velocity greater than that of the great sea wave, but less than that of the sound wave transmitted through the sea, and also much less than that of the sound wave through the earth, or of the great earth wave of shock; hence, after the first hollow sounds, carried by the earth, which accompany or slightly precede the shock, and before the approach of the great sea wave, a continuous succession of sounds, like the rolling of distant thunder, will arrive, first promptly through the water of the sea, and afterwards more slowly through the air, and when the origin of disturbance extends over a considerable line of territory, these sounds may continue even after the arrival of the great sea wave, which usually closes the terrible event. There can never be a sound wave through the air unless there be considerable fracturing of the earth's crust at the centre of disturbance. Very many other modified conditions, as to the arrival and continuation of the aerial, aqueous, and terrestrial waves of sound, will at once occur to those versed in acoustics, but which need not here be enlarged upon.

To recapitulate, therefore, *the order of the successive phenomena*, as they would present themselves to an observer upon the shore, we have the whole of the possible waves of every sort, viz., the earth sound wave and great earth wave or shock; the sound wave through the sea; the sound wave through the air; the

forced sea wave; the great sea wave; all originated at the same moment, or *quam proxime* so, by one impulse, and setting out together. The sound wave through the earth, and great earth wave or shock, arrive first, and are heard and felt on land, accompanied, as far as the beach, by the small sea wave, which I have called the forced sea wave; these are almost instantly succeeded by the sound wave through the sea; next arrive the aerial waves of sound, and continue to be heard for a longer or shorter time; and lastly, after a comparatively long interval, the great sea wave rolls in upon the shore, and the earthquake is complete; so far as all the phenomena belonging to one shock are concerned, it has passed through one complete phase. These, however, are generally repeated, but with diminished energy, each renewed impulse at the origin of disturbance renewing the whole train of effects.

I have only further to consider very briefly what will take place and be observable upon the shore *when the origin of the shock is not under the ocean bed, but upon dry land*, in the heart of a great continent, or anywhere far inland.

Here, then, the great sea wave is entirely absent; it can have no existence. The sound wave through the earth arrives first at the shore, or other distant spot, accompanied by the great earth wave, or true shock, which dips under the sea, and finally is lost beneath the ocean bed, or emerges, if sufficiently powerful, and produces a shock upon the shores of distant countries. At the moment that the earth wave plunges below the sea, if the shore be a beach, or shelving, a small forced sea wave will be produced, and thus a small, sudden, apparent recession of the sea, and sudden advance above its former level, will be observable; in fact, this phenomenon will be precisely the same, *mutatis mutandis*, whether the producing earth wave, pass from seaward to landward, or *vice versâ*. The forced sea wave will exactly keep pace with the movement of the great earth wave below, while the sea continues shallow, but as this deepens, and finally the earth wave gets beyond the edge of soundings, the forced sea wave will be no longer produced, and it will gradually subside and be lost.

Shortly after the passage of the earth wave or true shock, the aerial wave of sound produced by the eruption, fracture, or other original disturbance, will also reach the shore, and, passing off to sea, will finally become inaudible. These are all the wave phenomena which can occur, in general, in an earthquake

whose origin is inland; hence our theory shews that, in one respect at least, the common opinion is well founded, that all great earthquakes come from the sea; for besides that the earthquake whose origin is inland has, probably, always a smaller original impulse, because the disruptive forces, of whatever sort, are less opposed on land than they are under the bed of the deep sea, the inland earthquake always wants the desolating conclusion of the overwhelming great sea wave. The conditions, then, just enunciated are precisely what we find did actually occur in the great Calabrian earthquake. The centre of impulse was situated, according to Dolomieu, at the intersection of a line drawn from Cape Vaticano to Cape Colonna, with another drawn from Cape Suvero to Cape Stillo; it was, therefore, in the heart of Calabria. No great sea wave followed this tremendous earthquake on the Calabrian coasts, and yet the shock was powerful enough to pass under the sea, and destroy the city of Messina upon the opposite shore of Sicily.

Here there was, however, considerable agitation of the sea, the surges of which swept over the mole of Messina; but this was produced, we are told by Dolomieu, by waves generated locally, by the fall of an enormous mountain mass, which was broken off, and precipitated by the shock into the sea in the immediate neighbourhood of that city. A similar occurrence is recorded by Captain Basil Hall, I believe, as having occurred during an earthquake on the coast of South America, where an enormous mass of rock was observed suddenly to split off, and fall into deep water, producing a swell that was propagated and felt very far out to sea. In making observations during or subsequent to earthquakes, therefore, or in discussing their particular circumstances, with a view to discover the centre of original impulse, it will be necessary always carefully to ascertain whether great sea waves, observed at any point of the coast, have arisen from this or other such accidental event, or have come normally from the centre of impulse.

I proceed now to point out in what respects the theory of earthquake motion, which I have thus, I hope, been enabled to make intelligible, differs from all others previously brought forward, and to show how Michell's, which in some points appears most to resemble it (although the likeness is but apparent) fails altogether.

Michell's views, as to the agencies of vast regions of subterraneous vapour, pent up in a state of high elastic compression, seem to have been derived from

Bouguer, Don Ulloa, and other contemporary or slightly anterior authors. His hypothesis is, however, purely gratuitous; we have not a particle of evidence that any *large tract of the earth's surface* ever is afloat upon, much less buoyed up by, and elevated upon, vast masses of elastic vapour or gases. The only evidences we have of subterraneous vapour playing any part at all in the forces of elevation, are at the very foci of volcanic action, by the projection of solid masses from craters, the occasional splitting and blowing out of the sides of these, the spouting of geysers, &c.; but these, however grand when considered alone—"magna ista quia parvi sumus"*—are only minor phenomena in the great machinery of elevation of the earth's crust; and if any *considerable tracts* of surface, even in the neighbourhood of volcanoes, were afloat upon elastic vapour, rapid and perceptible falls of surface, ending with shocks, long continued and irrepressible blasts of the liberated gases, and other evidences of sudden depression, would be felt at those moments of the eruption when, by one of those mighty explosions, the caverns below were eased of their pent-up winds, and their roofs again dropped suddenly into contact with their molten floors. But no such facts have ever been observed; in all eruptions, however violent, the principal phenomena indicate the steady, upward pressure of liquid, but not æriform, matter from below: the pressure and all its effects are *hydrostatic;* and explosions, or sudden evolutions of elastic vapour, appear merely as the by-play, produced by the casual coming in contact of the heated materials with water, or with solids evolving vapours or gases by decomposition.

When the great rents at last open, liquid lava flows out, either quietly or attended with eructations of elastic matter; but these are disproportionately small in relation to the volume of liquid. Even when vast "crevasses" have opened up the bowels of volcanic mountains to their very bases, no great evolvitions of elastic matter have ever been recorded. Thus, in the eruption of Etna, in 1669, a fissure or "crevasse" of about six feet in width, and of unknown depth, suddenly opened in the plain of St. Lio, at the very base of the mountain, and ran up to within a mile of its summit—a fissure of twelve miles in length; it was soon succeeded by five others, nearly as large, and nearly parallel to it. Amidst the crash of riven rock, and rolling thunders from the hell below, heard forty miles

* Seneca, Ques. Nat.

away, a light of insufferable brightness, piercing the night, beamed up from these awful chasms, and heralded to upper air, the hissing lava. The molten mass, however, *slowly welled* up within the fissures, until its hydrostatic pressure at length gave it vent, and it flowed out at a distance of some miles at Monte Rossi. Here, then, where the mountain was ripped open from base to summit, no vast volumes of pent-up gases were liberated; no sudden depression of surface followed; nor am I aware that any such phenomena have been observed in other instances of eruption. We may, therefore, affirm that there is no ground in observed facts, for supposing large tracts of the earth's crust ever to float upon, or be elevated by, subterraneous seas of elastic gaseous matter.

There is, on the contrary, every ground for believing that the whole earth's crust does rest upon liquid melted matter, and that this crust, although of enormous thickness, is extremely thin in proportion to the vast depth from the surface to the centre of our planet. We cannot say what the absolute thickness is, but it probably is not less than forty-five miles. Now granting, *argumenti gratia*, that an original impulse is given to this solid crust, floating upon liquid lava, let us follow out the consequences, and see how far the production and propagation of such a wave as Michell has assumed, is possible in a crust resting on liquid matter, so as to agree with the known laws of wave motion, and the observed conditions of earthquake shocks.

His theory is, that the thin crust having received the original impulse at a certain point, undulates, by the passage of a wave not in the elastic plate itself, analogous to the vibration of a stretched string, or rather of a sonorous plate, but that the crust is *forced to undulate by the passage below it of a wave of the fluid* upon which it rests, so that the surface of the crust assumes the form, and follows the motion, of the undulating fluid below, in the same way as the carpet of his experiment follows the undulation of the wave of air below *it*. Now, we have shewn that the rate of transit of the great earth wave, or true earthquake shock, is immense, that it, at least, equals the velocity of sound in the same solids. The question then is, can a wave propagated under the conditions thus assigned by Michell, have any such velocity of transit?

Admitting, for a moment, that the crust of our earth bears any analogy to the flexible carpet of his experiment,—admitting that the enormous shell of, at least, forty-five miles in average thickness, could have flexibility enough to follow the

constraining motion of the wave of fluid upon which it rests,—then it follows that the speed of transit of the wave of fluid below, limits that of the undulating crust above—that the velocity of the earth wave or shock cannot be greater than that of the fluid wave below. Now the latter must follow the laws of a tidal wave—of the great sea wave of which we have already spoken; its velocity, like that of the tidal wave of our seas, will be a function of its length, and of the depth of the fluid, diminished, in this case, by certain considerations as to the density and degree of viscidity of the liquid; and although it would be at present impossible, for want of data, to calculate the exact velocity with which this subterraneous lava wave could move, it may be certainly affirmed that its velocity would be immeasurably short of the observed or theoretic velocity of the great earth wave, or true shock, in earthquakes.

Even if we suppose, as indeed would probably be the fact, that, the original impulse once given, there would be mutual constraint between the wave motions of the fluid below and those of the elastic solid crust above, so that the crust, if taken alone, would vibrate like a sonorous plate, while the fluid wave below it alone would follow the law of motion of a tidal wave, but that by their mutual reaction, a wave passes through both, having a common time of transit, or period of undulation, slower than that due to the vibrations of the solid elastic crush, but quicker than that due to the undulation of the fluid nucleus; still, the velocity of transit of the earth wave at the surface would be far too slow to answer the observed phenomena of earthquake shocks.

The rate of ascertained progress of the great Lisbon shock, the only one, unfortunately, that has been observed with any pretension to accuracy, is stated by Michell at *twenty miles per minute*, or 1750 feet per second*—a speed more than ten times that of the attendant great sea wave, and at least twenty times as great as it is possible to admit the velocity of propagation of a similar wave in imperfectly fluid lava; and yet this velocity is probably underrated, or, if not, the elasticity of the earth's crust must be greatly impaired by its increased

* Phil. Trans. vol. li. part 2, p. 572.—Humboldt (Cosmos), gives six to seven geographical miles per minute as the wave period of horizontal transit, without stating how this result has been obtained; yet he admits the vertical wave transit to have a period of vastly greater velocity, as, for instance, in what he calls the "upward explosions" at Riobambe, which projected the bodies of the inhabitants nearly 100 feet. It would be an important fact if future observation should prove a different wave period for the same formation in the vertical and horizontal directions.

temperature due to depth. Thus, then, granting the whole of Michell's hypothesis, we find the inevitable results of his own theory will not square with observed facts on the one hand, nor with the decrees of physics upon the other. It would be, therefore, needless to discuss more at length the gratuitous and unsustainable character of his hypothesis as to the mode of production of the original impulse itself.

It remains, then, to explain a little more fully the precise nature of the great earth wave of elastic compression assigned by me as constituting, by its transit, the earthquake shock, and to explain briefly the general mode of origination of the impulse by which it is produced, or at least may be conceived to be produced, without the assumption of any hypothesis beyond the established facts, that forces of some kind, acting from below upwards, produce local elevations of portions of the earth's solid crust, often attended with dislocation and fracture of the crust, and sometimes attended with the actual outpouring of liquid matter from beneath; that these elevations take place with various degrees of rapidity, sometimes continuing to lift the land slowly for many years, as in Norway and Sweden; at other times producing an upheaval of several feet in a very short time, and that such elevations occur both on land and beneath the ocean.

In such local elevations, then, I find the efficient cause of the earthquake shock, which I define to be *a wave of elastic compression, produced either by the sudden flexure and constraint of the elastic materials forming a portion of the earth's crust, or by the sudden relief of this constraint by withdrawal of the force, or by their giving way, and becoming fractured.*

When a portion of the solid crust of the earth, whether consisting of stratified or of igneous rock, is urged by forces of elevation from below (of whateve sort), having a certain definite elasticity and flexibility, the whole plate of solid material above may be viewed as a platform or beam, supported or held fast at the edges or ends, and loaded or pressed upwards, more or less uniformly, from beneath. If the platform or beam bend under the strain, all the particles below a certain *neutral plane* will be thrown into a state of compression, those above it into the opposite condition of extension; and if this bent and constrained condition of the plate or crust be suddenly produced—if the pressure from below be suddenly brought upon it, *a wave of elastic compression will, at the moment of flexure, be produced,* and propagated at once in every direction outwards from the fixed edges of the plate, or through the surrounding portions of country

which have not partaken of the elevation. This wave will be negative above the neutral plane, and positive below it.

Again, after the plate or crust has been so elevated, whether quickly or slowly, *if the constraining forces be suddenly relaxed*, so that the plate, like a bent bow, is permitted to become straight again, that is to say, drops down from its state of flexure to its former level, or partially towards it, the resilience—the sudden return of the extended particles above the neutral plane, and of the compressed particles below it to their condition of repose—will produce and propagate in all directions *a similar wave of elastic compression*, which will be positive above the neutral plane, and negative below it. Thus, sudden elevation, or sudden depression of a tract of country, must always be attended with the production and transit through the surrounding crust, whose level has not been disturbed, of an elastic wave, or true earthquake shock, even although not preceded in either case by dislocation or fracture of the rocky crust; the amount of extension and compression of the particles above and below the neutral plane having been, in these cases, within the elastic limits of the particular rocks constituting the elevated crust.

But again, the elevating forces may act rapidly, as in the case of Monte Nuovo, elevated 440 feet in forty-eight hours, in 1538, and continue to act until, at length, they *do* produce fracture and dislocation of the crust above; or they may act very slowly, yet continuously, and at last produce fracture and dislocation. In the former case, one wave of elastic compression will be produced at the moment that the rocky crust is suddenly bent; and another, and much greater one, at the moment that fracture takes place by its giving way, and the constraint of the extended and compressed particles is thus released. In the latter case, namely, of very slow elevation ending in fracture, there will be no earth wave, and no shock until the fracture actually occurs.

When the earth wave impulse arises from sudden elevation, or sudden depression, of a local district, within its elastic limits, and therefore not accompanied by fracture, the earthquake shock will be felt at a distance; but there may be no noise heard, no previous or subsequent rolling sounds in the earth.

When fracture occurs, on the contrary, the awful noise (the "*bramidos i truenos*" of the Spanish Americans) will be heard, and, as already explained, may precede, continue during, and be heard after, the shock reaches a distant point.

In the former case also, viz., impulse by sudden elevation or depression, with-

out fracture, the earthquake may commence by very gentle shocks, gradually increasing in violence, and again diminishing in force.*

Where the elevated crust consists of horizontally, or nearly horizontally stratified rock, or of several parallel superimposed masses of independent rock, of whatever sort, those that lie deepest will be first and *most* bent, and, *ceteris paribus*, will be the first to give way by fracture; those above them will break in succession, and when the area and amount of elevation are very great, each layer or plate of the whole elevated crust may be fractured successively at several places, so that from a single locus of elevation a number of earth waves may be produced and propagated in succession, each constituting a true earthquake shock: nay, even after numerous fractures have taken place, the further upheaval and tilting over of vast masses of the now broken up plate will, where its thickness is considerable, produce renewed mutual pressures and violent constraint, in the directions of the diagonals of the several tabular blocks, which will afterwards give rise to minor shocks, as in the further progress of elevation, the several masses of the ruptured crust are raised and freed from each other, and the compression and constraint of their elastic particles thus successively removed. (Plate II. fig. 8, α. β. γ. δ., and Description of Plates).

Where successive fractures at different, but great, depths, take place in this way, two distinct systems of elastic waves, one of them having a vertical, and the other an horizontal or largely inclined direction of transit, will traverse the mass of the earth's crust, and be felt upon its surface at once; but the amplitude of the waves of the former system will be very small, as compared with the waves of the latter, and hence an undulating and oscillatory motion will be experienced at the surface, accompanied by a sharp upward jar or vibration at the same time,—circumstances which have been occasionally recorded as having been observed during earthquakes.

Such, then, I conceive to be the true origin and nature of the earthquake shock. It is produced by any force which disturbs the equilibrium of elasticity of the materials constituting the crust of the globe, and it is propagated from the locus of its origination, in accordance with the laws of transit of elastic waves through such materials.

* See Alison's Account of the Chilian Earthquake, in February, 1835, Geol. Trans.; and Caldcleugh's Account, Phil. Trans. for 1835.

Two points remain, therefore, to be briefly considered, viz., what will be the *velocity of transit of an elastic wave*, so produced, in the various sorts of rock with which we are acquainted in the crust of the earth, and what will be the possible elevation of the crest, and what the amplitude or length of the wave so produced.

If our knowledge of the moduli of elasticity and of cohesion, of the various beds of softer or harder minerals, constituting the whole depth of loose or rocky crust of our globe, were perfect, we should be in a condition to answer these questions more perfectly; unfortunately, however, no moduli of elasticity have been ascertained for mineral substances, with the exception of a very few, determined for the use of the engineer or architect; these few I have tabulated below. Scanty as they are, they suffice to illustrate the truth of our theory, and to shew that, at this point, mathematics and physics can hereafter render the most direct and important services to geology.

	Modulus of Elasticity.	Extensibility before Fracture.
Cast iron,	5.895.000	$\frac{1}{1204}$
Wrought iron,	7.550.000	$\frac{1}{1400}$
Steel,	9.300.000	
Glass,	4.440.000	
Limestone (maximum),	2.400.000	
——— (minimum),	635.000	
Yorkshire sandstone (millstone grit),	1.320.000	
Slate, (Leicestershire),	7.800.000	
White marble,	2.150.000	$\frac{1}{1394}$
Portland stone,	1.570.000	$\frac{1}{1789}$
Lead,	. . . .	$\frac{1}{480}$

Referring to this table, we find, to take an example, that a mass of primary limestone will extend, before fracture, $\frac{1}{1394}$ part of its length; or, in round numbers, that every 1400 feet in length of a plain of such limestone may, by being bent into a curve upwards by any adequate force, be stretched one foot in length before rupture takes place any where; hence, if an area of only five miles in diameter, consisting of primary limestone, be elevated by any force whatever, acting from beneath, its surface will be extended or stretched no less than eighteen feet, or rather more, before fracture takes place, and this, whatever be

the depth or thickness of the crust or bent plate. This amount of extension will decrease as we descend, until it reaches the neutral plane, where it will be evanescent, and at which point compression commences, and which will probably be equal to the extension above, at equal distances below the neutral plane. Now, at the moment that fracture takes place, and the particles are released from this their state of constraint, as action and reaction will be equal, a wave of elastic compression will spread itself in every direction from the surfaces of fracture, and will pass through the substance and surface of the adjacent country, until finally lost and obliterated, owing to the imperfect elasticity of the masses composing it.

The amplitude of this wave at the surface will be, *quam proxime*, half the amount of elastic compression or extension due to the substance, and to its dimensions; thus, in the case assumed, the amount of lateral oscillation or amplitude of the great earth wave or shock will be about nine feet at the surface of the surrounding country.

As homogeneous elastic bodies are equally elastic in all directions, and as the earth's crust is free to expand upwards, but not downwards, at least not nearly to the same extent, so the transit of the elastic wave will be attended with an actual undulation of the surface of the country, at the point of transit of the elastic earth wave; for every compression or extension of particles in the horizontal ordinate must, in its reaction, produce corresponding extension and compression in the vertical; hence, the vertical height of the wave of horizontal transit will depend upon the elasticity and the depth of the rock through which the wave passes.

We have thus shewn that the dimensions of the wave producible by the elasticity of the earth's crust are fully sufficient to answer the facts observed in earthquake shocks: the example I have given is a mean case; for harder and more elastic rocks the amplitude of the wave will be less, its transit velocity greater; and for formations of less hardness and elasticity, the amplitude greater and the transit speed of the wave less.

But we have further to consider the actual rate of progress of such a wave through the solid crust of the globe. This, which may be called the *specific period of wave transit*, will vary for each formation, and depend upon the specific elasticity of the mass considered as uniform, and probably, also, in some degree, upon its depth. The velocity of transit will be the same as that of sound in

the same substance, or, in general, of any force whatever transmitted by pulses.

Here, again, we want numerical data. Hassenfratz and Gay Lussac observed, in the quarries under Paris, that sound travels with immense velocity in rock, and the same observation has been made in blasting the rocks in the Cornish mines; but no *measures* of its velocity have been ascertained, and the only trustworthy measurements we possess, of the velocity of sound in any mineral solids, are those obtained by Biot, as to the time of wave transit through cast iron. He found, as has been previously stated, that sound is transmitted through cast iron at the rate of 11,090 feet per second.

If we take the modulus of elasticity for the following rocks from the preceding table, and comparing these with the modulus of cast iron, suppose the time of wave transit in each to be proportionate roughly to the square roots of their respective moduli, we get the following table of results for the specific period of the great earth wave, or shock, through the several sorts of rock formation.

	Period of wave transit, or velocity in feet per second.
Limestone (soft Lias),	3640
Sandstone (millstone grit),	5248
Portland stone (oolite),	5723
Limestone (primary marble),	6696
Limestone (hard carboniferous),	7075
Clay slate (Leicestershire),	12757

Comparing these numbers with the observed speed of the great Lisbon earth wave or shock, namely, 1750 feet per second, we find that the result agrees sufficiently, making allowance for the loose superficial deposits in which the period of the Lisbon wave was observed, and for the retardations produced by breaches of continuity therein. Let it be understood, however, that no present importance attaches to any of these numbers, which are all but crude approximations, and to be viewed as mere illustrations of the application of my theory, rather than as proofs of, or deductions from it.

When correct data shall have been obtained, when we have found the moduli of elasticity, and of cohesion, and the limits of extensibility, for all our great rock formations, and the changes produced in these by augmentations of temperature,—a work capable of easy performance, but requiring multiplied

experiments upon different specimens from every known formation of rock, in order to get the average result for each formation,—and when, in addition, the actual time of transit of the great earth wave or earthquake shock shall have been accurately observed, over long ranges, in various formations, and with suitable instruments and precautions, then shall we be in a position not only fully to verify the truth of this theory of earthquake motion, but able also to deliver into the grasp of the computist, a wide domain of physical geology, hitherto an unprofitable waste of uncertainty and conjecture.

We may notice a few of the more direct applications to geology which may be made of our theory, whenever such data are obtained.

However well modern geologists have surveyed and mapped the formations constituting the land which we can see and handle, of the nature of the bottom of the great ocean we know nothing; no human eye ever has or ever can behold it; we cannot even reach its deep abysses with the sounding line; yet the ocean covers nearly three-fourths of our entire globe, and of this vast area the geology is an utter blank. If, however, we are enabled hereafter to determine accurately the time of earthquake shocks, in their passage from land to land, under the ocean bed, we shall be enabled almost with certainty to know the sort of rock formation through which they have passed, and hence to trace out at least approximate geological maps of the floor of the ocean. For, knowing the time of transit of the wave, we can find the modulus of elasticity which corresponds to it, and finding this, discover the particular species of rock formation to which this specific elasticity belongs.

It is needless to enlarge upon the value to geology of even a very general knowledge of the nature of the great ocean beds. Perhaps no single circumstance has more retarded our forming distinct perceptions of the great changes, hourly occurring, as to the forms and boundaries of sea and land, or which have, at past epochs, taken place, than the impossibility of seeing the geological map of the world as a whole. The land, or rather a few fragments of the land, alone, we have seen, the ocean shrouds the vast remainder; and the imagination can no more seize the traces of successive cataclysms, or of the slow but ever-acting agencies, by which our globe has been changed and remodelled, by this partial and imperfect glimpse, than the statuary could judge of the proportions of the muffled figure that presented but part of a single limb to his view.

But again, as the height or elevation of the great earth wave is a function of the depth of the solid elastic crust which has been put in motion, future accurate observations of this coefficient will enable us to determine the actual depth from which earthquake dislocation has come, and to which it laterally extends.

This would throw light upon the otherwise inexplicable facts observed at various periods, namely, of earthquake shocks being felt at a given depth, and not at the surface of the same place, and *vice versâ*. Thus, in 1802, the miners in the deep silver mine of Marienberg, in the Hartz, were frightened from their work by a shock which was not perceived by those at the surface; while, in 1823, the surface shocks felt at Fahlun, in Sweden, were not perceptible under ground. Whatever be the depth of the plate, or band of rock, originally disturbed or constrained, the same will be the depth to which the lateral transit of the earth wave will be principally confined. Hence, if the original impulse is deep, the shock will be, in some degree, limited to the same plane of level,—if superficial, the shock will not extend in depth.

Again, the amplitude of the wave bears a relation to the diameter or extent of the area of original disturbance, or centre of impulse; and hence, observations as to this dimension of the earth wave will give some approximate information as to the area of original disturbance, though, perhaps, buried profoundly in the ocean.

Other, not less interesting, but less immediate, deductions will occur, in which this application of physics and mathematics to geology may explain some of the most obscure and perplexing marks of former movements in the earth's crust that we now behold. Who can explain at present the straight line course, held on for miles by faults and dykes, often cutting equally through every formation they cross at the surface? Who can give a plausible solution of the fissures which traverse the coarse conglomerate of the south of Ireland, cleaving with a perfect plane, like a sword-cut, through the great quartz pebbles, and through the softer cement, alike regardless of changes of texture or of hardness in the mass? May not these, as well as many of the greater fissures now constituting mineral veins, be the evidences of dislocation produced by the passage, from enormous depths, of elastic waves, whose times of transit have been suddenly altered, by passing from one formation to another, at depths altogether below our observation or means of present knowledge, *lines of broken unison*, in

fact, in waves that have originated altogether below the ken of our upper world?

While the facility with which one class of our data may be ascertained will be disputed by none, it may, perhaps, occur to some that, as earthquakes are happily rare, and give no notice of their advent, and moreover, are times of such consternation, so but little accuracy is to be hoped for in observations, as to the speed or circumstances of the shock, made during such visitations. This might be partly true, were we dependent upon the nerve or watchfulness of individual observers; but already attention has been given to the contrivance of self-acting instruments (and instruments, though by no means well devised nor self-registering, have been already in use in Scotland, and perhaps elsewhere) for the registration of earthquake shocks; and there can be no doubt that, by *earthquake observatories*, established, with suitable instruments, at distant localities, in South America or Central Asia for instance, where earthquakes, greater or less, are of almost daily occurrence, a very complete knowledge of the time of wave transit, and of the amplitude and altitude of the earth waves for given districts, would be soon obtained. No instruments for ascertaining the latter have been yet proposed, but they do not seem by any means difficult to devise. It is almost certain that minute earthquake shocks frequently pass through almost every part of the earth's surface, so slight as to remain unnoticed for want of instruments to detect them. In February, 1822, a slight shock of an earthquake was felt at Lyons, in the south of France; it was not perceptible generally at Paris at all, yet the wave reached and passed beneath that city; for M. Arago, who was engaged at half past 8 o'clock in the morning in his magnetic observatory, found that his large magnetic declination needle, which was previously quite at rest, suddenly began to swing like a pendulum in the direction of its length, viz. north and south; and M. Biot, who was at his residence in the College de France, observed other analogous phenomena there.* It would, therefore, seem very desirable that suitable instruments for earthquake registration were, at least, added to all the magnetic observatories now so widely extended over the earth, accompanied by proper instructions to the observers,—unless, indeed, separate *geological observatories be established in favourable localities for taking cognizance of all movements of the earth's crust.*

* See Comptes Rendús.—Prof. Lloyd has also, at a subsequent period, very frequently noticed such phenomena at the Magnetic Observatory of the University of Dublin.

But another, and much more rapid, and perhaps even certain, method, remains to be noticed, for obtaining part of our data as to the *specific period of wave transit*, viz. *by direct experiment*, which in all matters of inductive science may be pronounced, whenever it is possible, better than mere observation.

I have already stated that it is quite immaterial to the truth of my theory of earthquake motion what view be adopted, or what mechanism be assigned to account for the original impulse ; so, in the determination of the time of transit of the elastic wave through the earth's crust, if we can only produce a wave, it is wholly immaterial in what way, or by what method, the original impulse be given.

Now the recent improvements in the art of exploding, at a given instant, large masses of gunpowder, at great depths under water, give us the power of producing, in fact, an artificial earthquake at pleasure ; we can command with facility a sufficient impulse to set in motion an earth wave that shall be rendered evident by suitable instruments at the distance, probably, of many miles, and there is no difficulty in arranging such experiments, so that the explosion shall be produced by the observer of the time of transit himself, though at the distance of twenty or thirty miles, or that the moment of explosion shall be fixed, and the wave period registered by chronometers, at *both* extremities of the line of transit.

For this alone very moderate charges of powder will answer, but if the explosion be made out at sea with sufficient energy, there will not only be produced the transit of the earth wave and the sound waves through the sea and air, but the accumulation and subsequent coming in of the great sea wave, so that all the phenomena of the natural earthquake are thus placed within our power of production, observation, and control.

These are experiments, the value of which, to general physics as well as to geology, will be admitted ; but they cannot be made without the aid and appliances which our Government can afford, through the Admiralty and Royal Engineer departments. It cannot be doubted, but that application made for such assistance, through the Royal Irish Academy, or some other of our learned bodies, to the proper authorities, would meet with a favourable reception.

It is to be remembered, however, that these direct experiments can only give the time of wave transit for the substances forming the very uppermost crust of

the earth. That earthquake shocks often come from profound depths is in a high degree probable; and while down to a certain depth we may expect to find the density and elasticity of the earth's crust continually increasing, below this again, we must suppose the mineral masses in a more and more softened or even pasty condition, as they approach the lower fluid region, and hence possessed of lower elasticity. While, therefore, we cannot draw direct conclusions as to the time of transit of the wave in the rocks thus circumstanced at profound depths, from its time of transit in the solid rocks or superficial deposits of the surface, we may reasonably expect to derive information as to some of the physical characters and molecular condition of the deep rocks themselves, by comparing observations of the actual time of wave transit of natural shocks, coming from great depths, with that of natural or artificial shocks traversing at the surface or near it.

On the other hand, when the modulus of elasticity has been determined for the principal rocks, at various temperatures, augmenting up to their points of fusion, and the same data have been obtained for them in a fluid state, we shall be in a position to demand assistance from the mathematician in determining the complex conditions of horizontal and vertical wave motion in a *compound mass*, solid at the surface, and increasing in density and elasticity down to a certain depth; below this gradually becoming a pasty semi-fluid mass, with probably still increasing density, but diminishing elasticity; and finally becoming a dense elastic liquid susceptible of fluid wave movements, at still profounder depths.

Such a question can scarcely be attempted after the data, already alluded to, have been obtained, without our deriving some additional knowledge as to the constitution of the interior of our planet.

In the progress of this inquiry, and in consulting very many accounts of earthquakes, one thought has been constantly suggested to me, which, although not directly belonging to the subject of this paper, may be very briefly noticed. While every part of the earth's surface appears occasionally liable to earthquakes, and while volcanic countries are peculiarly so, though by no means remarkable for being visited with those of greatest violence, the origin, or centre of disturbance, of almost all the greater earthquakes appears to be beneath the sea, and at considerable distances from active volcanoes, as already observed. At the same time, the circumstances of the great sea wave seem to indicate that the centre of disturbance is seldom, if ever, *very* distant from the land. May it not, then, happen that the

great general region of local sudden elevation, within which we are to look most commonly for the earthquake's origin, exists as a broad belt surrounding the land; within this belt all the diversified deposits of the detritus of the land are constantly taking place, shifted and modified subsequently by tidal currents, &c.; hence, within this space the isogeothermal planes are in a constant state of fluctuation, now rising, where a thick coat of badly conducting matter is locally deposited, and again rapidly sinking as it is swept away. Such a condition of the sea bottom would seem to be the most likely state of things to give rise to frequent and sudden local elevations, or even submarine eruptions of molten matter, as has been well explained by Herschell and Babbage.

Since writing the preceding pages, and not before, I have been enabled to read the portions of Humboldt's Cosmos which treats of earthquakes. On opening this book I fully expected to have found my views anticipated by the great German philosopher. In this, however, I find I was mistaken. While admiring the exuberance of facts, the copious sources of far-drawn observation of the veteran traveller, I was disappointed to find that Humboldt had not even made the attempt to frame a theory of earthquake motion. He notices the transit of the shock as of waves of some sort (as many others have done before), and even suggests their production at centres of disturbance, and hints at their having some connexion with the elasticity of the rock through which they pass, and at their possible mutual intersection and interference; but it is impossible to discover (throughout the whole chapter) that he has formed any distinct idea as to the nature or mode of propagation of the great earth wave. At one place the reader is led to fancy that he speaks of the wave of elastic compression in the solid crust, which I contend to be the true earthquake wave; but again, in finally summing up his views, he seems completely to adopt those of Michell. He says, "the filling up of fissures with crystalline matter interferes by degrees with the free escape of vapours, which, confined, become operative through their tension in three ways, *concussively*, *explosively*, or suddenly up and down, and,

as first observed in a large portion of Sweden, *liftingly or continuously*, and only in long periods of time perceptibly altering the level of the sea and land."*

He does not attempt to assign the law of motion of any one of the several orders of earthquake waves. The shocks, also, he describes as either horizontal and vertical, or *rotatory* and *vorticose* in direction ; the two former, he says, are almost always observed together, the latter is rare; and instances the Calabrian obelisks, &c.; but, like all preceding writers, he leaves the subject without an attempt at explanation.

He also gives, as another instance of vorticose or rotatory movement, the twisting of the previously straight furrows of ploughed fields, in the Calabrian plain, as recorded by Dolomieu ; confounding, in this case, the distortion produced by the slipping of the soil over an inclined and twisted bed upon which it reposed, with the true rotation of the obelisks, &c., the real nature of which I have already explained.

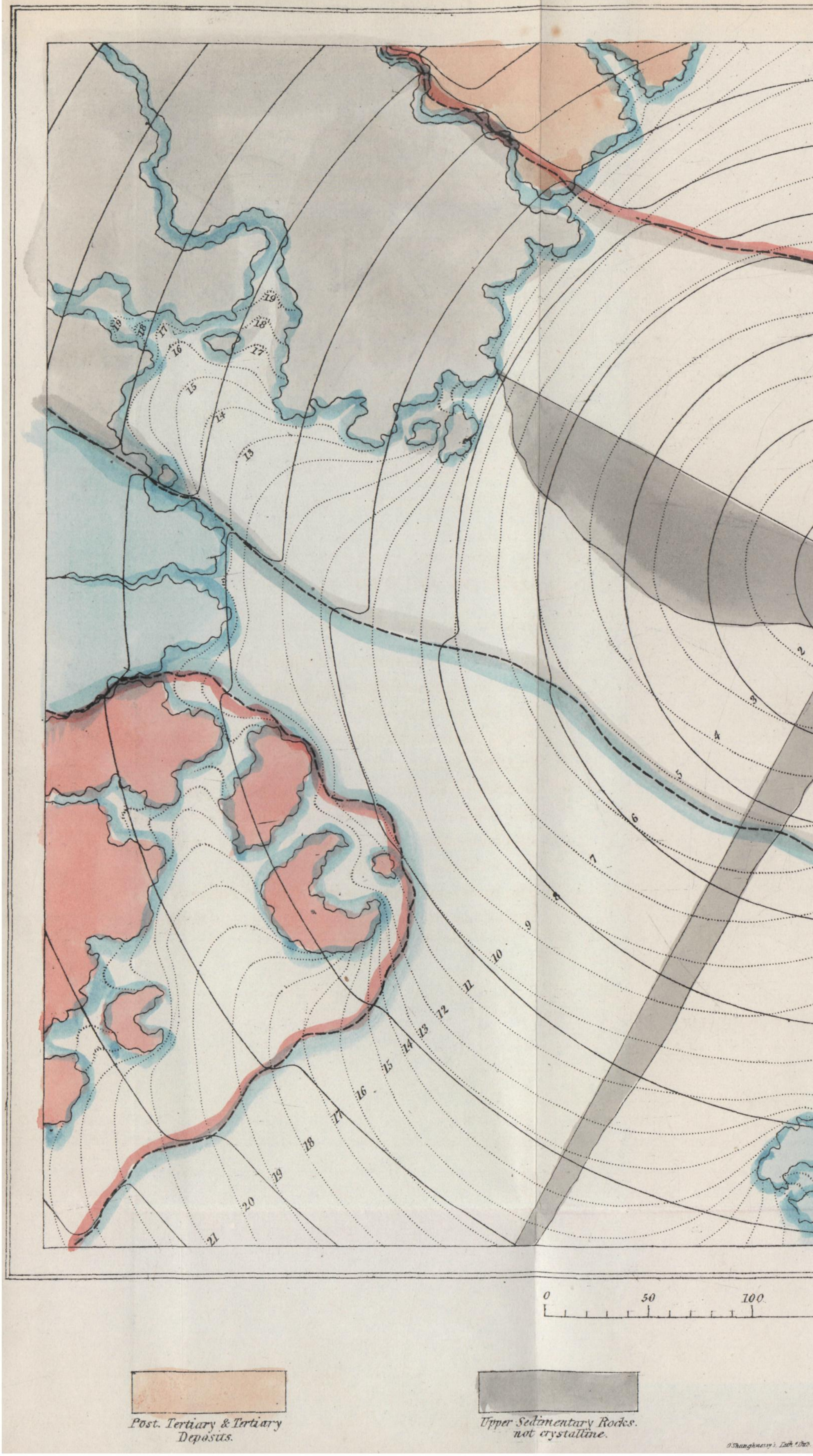
When, however, we find Humboldt† seriously ascribing the dome-shaped forms of the Puy de Dome and of Chimborazo, to their being *hollow bubbles* of trachyte or dolerite, *blown out by elastic vapours* at some former period, we see the evidence that the greatest minds may be captivated by a favourite fancy, and feel no surprise at his adoption of the untenable, but analogous theory of Michell, if, indeed, such BE his view, for he leaves the subject in entire doubt. Whilst it is impossible to discuss at length the views of Humboldt, at the termination of a paper already far too long, I have deemed it necessary not to pass unnoticed the opinions of one whose authority is so generally reverenced.

In having thus attempted the treatment of a vast and difficult subject, I may, perhaps, at times have appeared to some to wander into the regions of mere scientific speculation or romance. I am not conscious of having done so, but if I have, it is pleasant to be sustained even there, and the value of occasionally giving rein to the imagination asserted in such words as the following, uttered by a Humboldt:

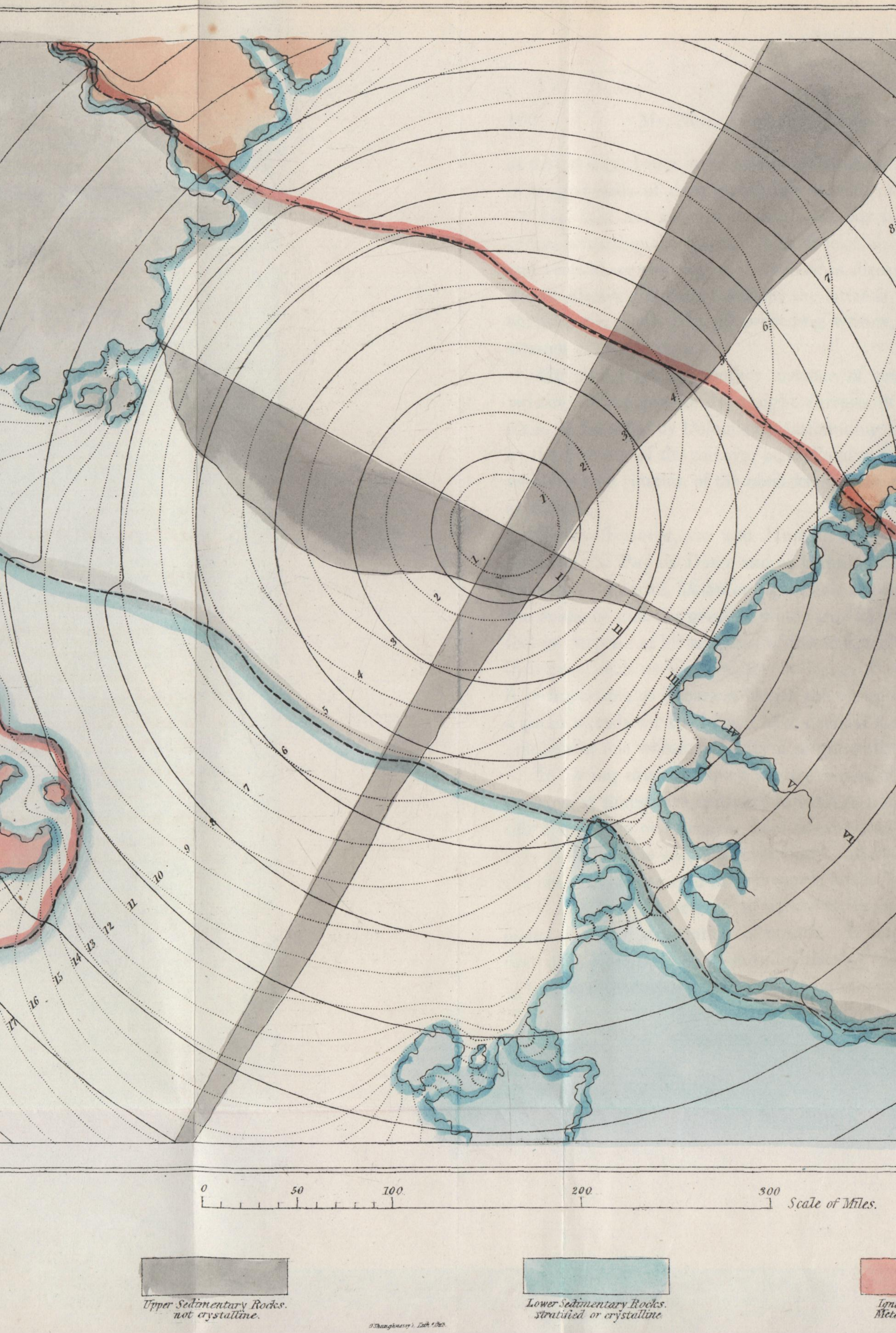
"A philosophic science of nature strives to rise beyond the limited requirements of a bare description of nature. It consists not in the barren accumulation of isolated facts; the curious, the inquiring spirit of man must be suffered to make excursions from the present into the past, still to surmise what cannot be

* Pages 224–226. † Page 238.

MAP OF EARTHQUA

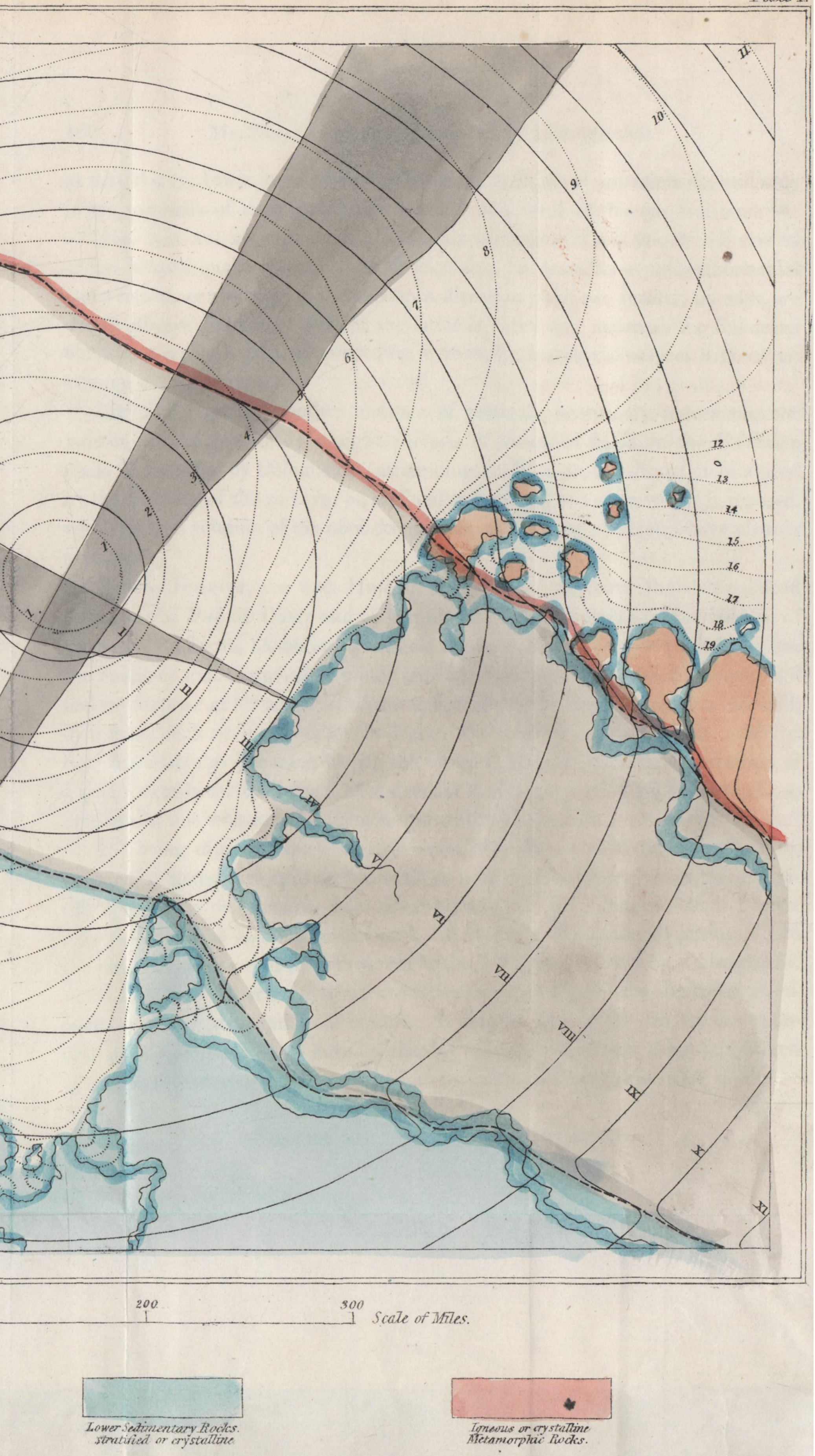


MAP OF EARTHQUAKE COTIDAL LINES.



KE COTIDAL LINES.

Plate I.



possibly known, and to revel in the old and, under various shapes, ever-recurring *myths* of geognosy."*

It is to be wished that something more of this spirit were transferred to the fact-worshipping geologists of our day.

Geology, like every other department of inductive science, to be successfully pursued, must at times be followed by the high *a priori* road; an elevation must be attained which, without superseding the collection and the colligation of facts, shall enable us to look down upon and explain them, by seeing their order, connexion, and agreement with the laws of mechanics, physics, and chemistry.

DESCRIPTION OF THE PLATES.

Plate I.—Map of Earthquake cotidal Lines.

This represents an imaginary portion of the earth's surface, the seat of earthquake disturbance; the forms of the coast, the depth of soundings, and the geological formations of the land, have been arranged for the purpose of evidencing, through the eye, the relations, to them and to each other, of the elastic earth wave or shock, and of the great sea wave.

The uncoloured portions of the map represent the sea, the depth of soundings of which are given in two sections, intersecting at right angles, through the point which is the origin of the earthquake impulse. These sections, coloured dark grey, shew, by the method commonly called "sectio-planography," the depths along the right lines forming their upper boundaries, which are on the surface of the water.

The land and the bottom of the intervening sea are supposed to consist of four distinct formations, or rather classes of formations, differing in depth and in elasticity, viz.:

1. Post-tertiary and tertiary deposits. Coloured Yellow.
2. Upper sedimentary, non-crystallized rock. Coloured Gray.
3. Lower sedimentary rocks, either stratified, laminated, or crystallized. Coloured Blue.
4. Igneous or metamorphic, crystallized rocks. Coloured Red.

Each of these classes may combine several groups of formation, but it is supposed that the properties, as a whole, of each class, as to elasticity, &c., are in the above order, proceeding from the least to the most elastic.

* Page 252.

The lines of junction of these groups are indicated by a strong, dotted line, coloured according to the formation at either side thereof.

The centre of impulse, or of earthquake disturbance, is supposed to lie under the bed of the sea, at a point directly beneath the intersection of the sections of soundings.

The dark, continuous, and nearly circular curves, represent the crest of the earth wave of shock, at successive small intervals of time, as it traverses each of the formations of the map, starting from the centre of impulse; and the fine dotted curves represent the crest of the great sea wave, at similar successive small intervals of time, in its progress towards the surrounding coasts. The surface lines of the sounding sections thus may be viewed as ordinates of time, along which these wave crests may be supposed to move.

On examining the cotidal curves for the earth wave, it will be remarked that, starting from a single point in the upper sedimentary rocks, they are perfect closed circles, so long as they continue in the original formation; but as soon as they pass the junction at one side, they begin to move faster, or have a larger space interval in the crystallized and more elastic lower sedimentary rocks, while, at the other side, having penetrated into the superficial formations (post-tertiary and tertiary) of lower elasticity, they move more slowly, and with a less space interval. Again, when passing from the lower sedimentary into the igneous rocks, they reach a formation of still higher elasticity, the earth wave crest shows a still greater augmentation of velocity. At the junction of the several formations, therefore, the earth wave curve suffer a sudden flexure, produced by the sudden change of velocity; and at these points the direction of transit of the earthquake shock not only differs from that at either side of the junction, but continually changes along the same line of junction in the progress of the wave. Thus, the earth wave, at the interval IV., traverses the junction of the upper and lower sedimentary formations (to the south-east of the map), in a direction nearly due south; but as it passes through the same junction at the intervals V., VI., VII., VIII., IX., X., and XI., it continues to pass through successive points of the compass, until, at X. and XI., its transit is made in a direction nearly north-west, and almost at right angles to the direction of shock, closely adjacent, within the two formations at either side of the junction. Other similar apparent anomalies will be obvious, upon a careful inspection of the earth wave curves on other parts of the map. These curves, of course, only represent the crest of the *principal* earth wave. At every sudden flexure there will be many minor divergent waves.

Referring, now, to the (dotted) cotidal curves of the great sea wave, it will be remarked that, as the progress of this wave depends upon a function of the depth, so the originally closed and nearly circular curves of the great sea wave become more and more distorted, by its transit through the variable depths of the sea, moving with great rapidity in the deep water, and here showing a large interval, but moving more and more slowly as the water shallows near the coast and in the estuaries.

It results from this, that the direction of the great sea wave, on its arrival at a dis-

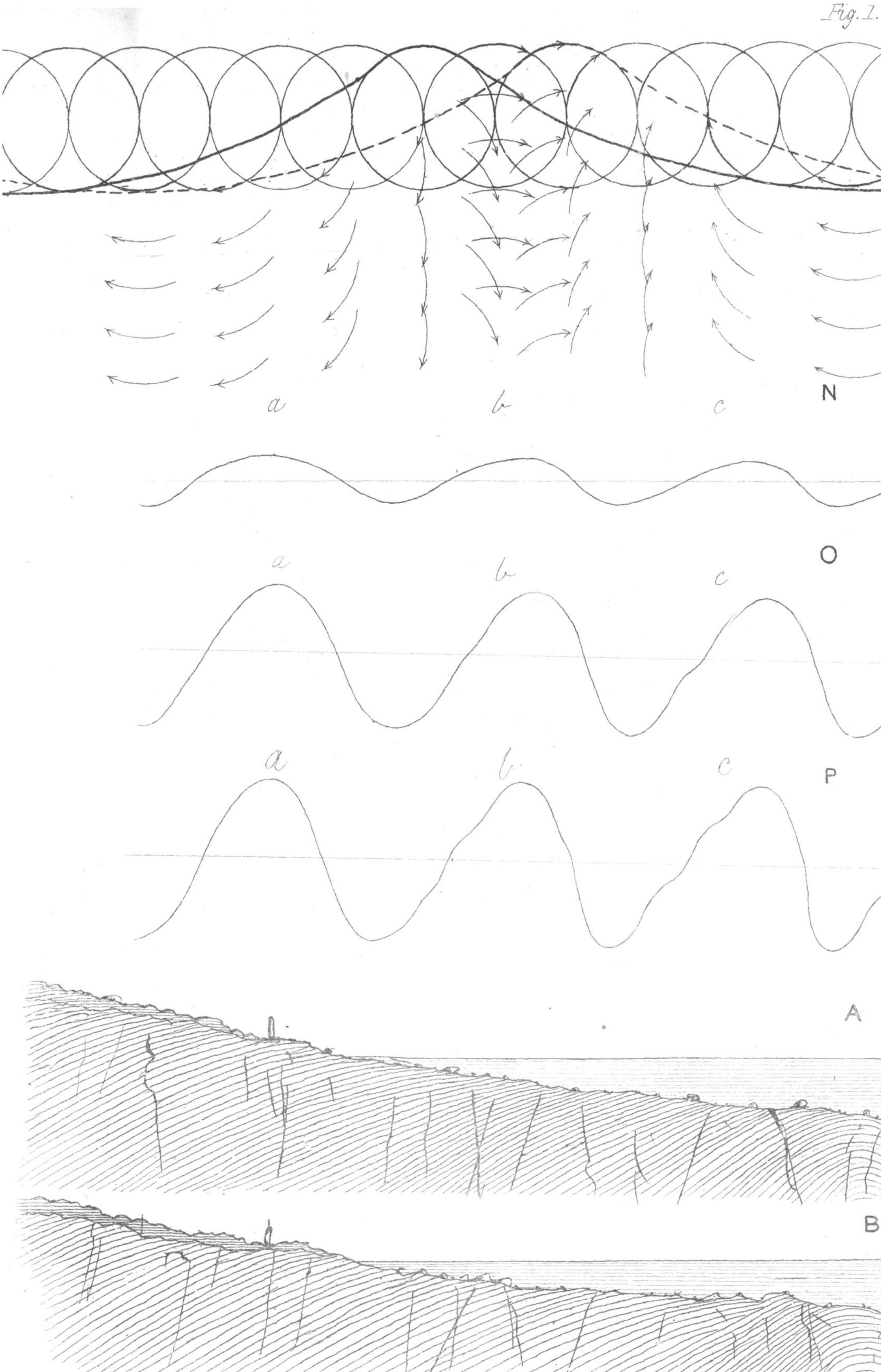

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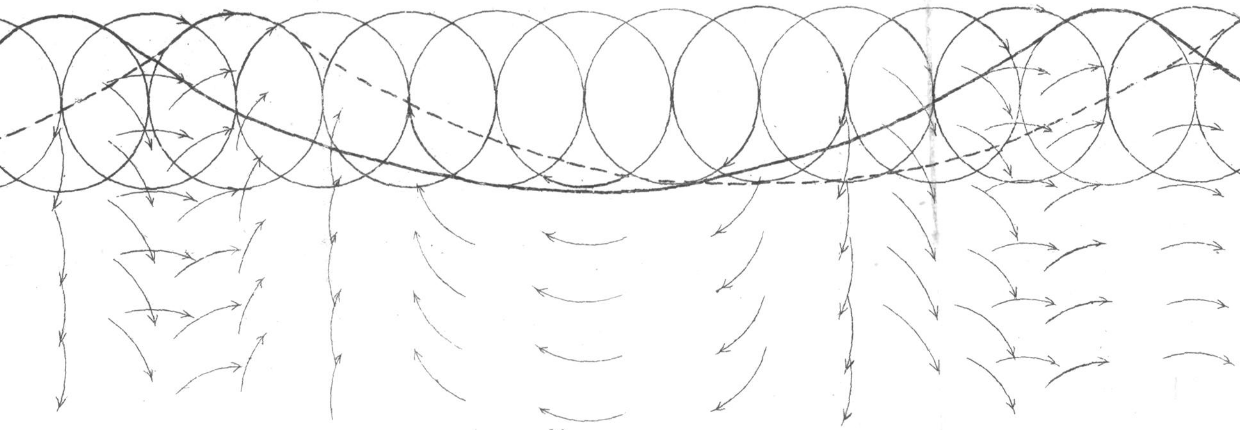
Fig. 1.



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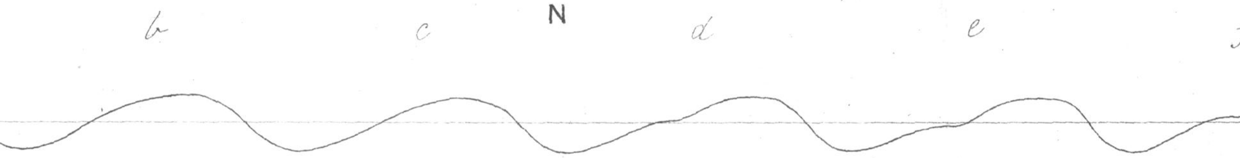

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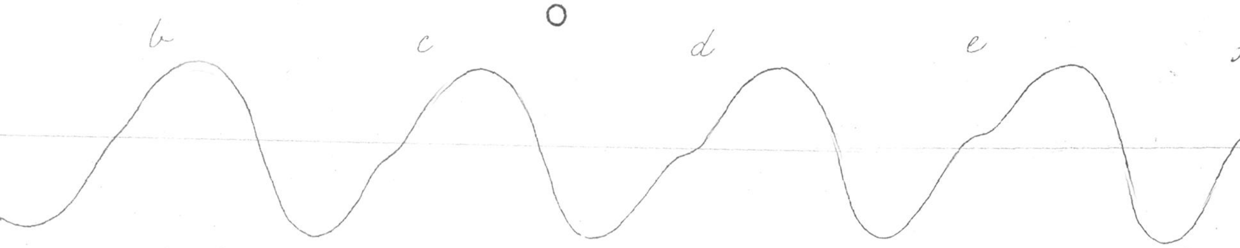

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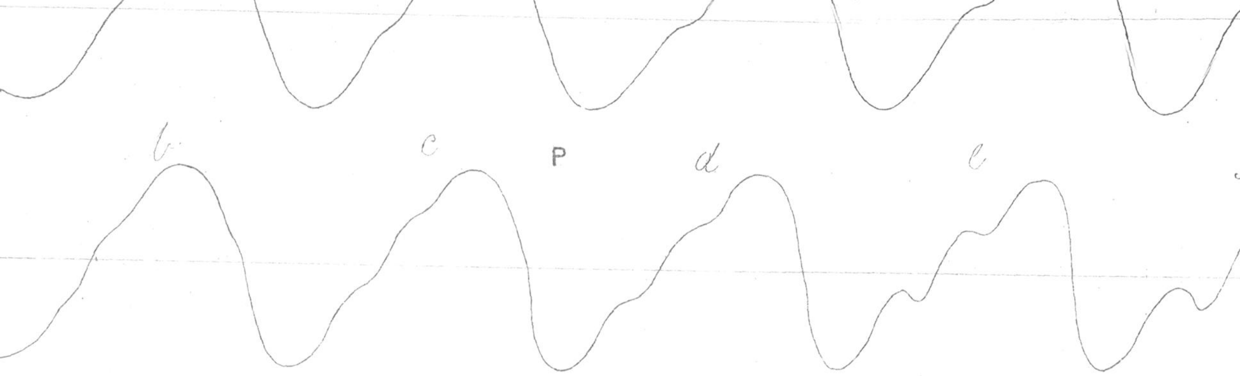

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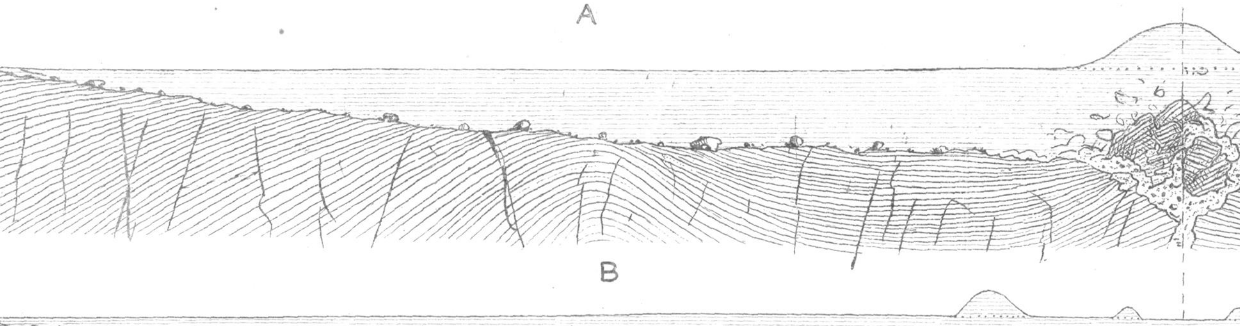

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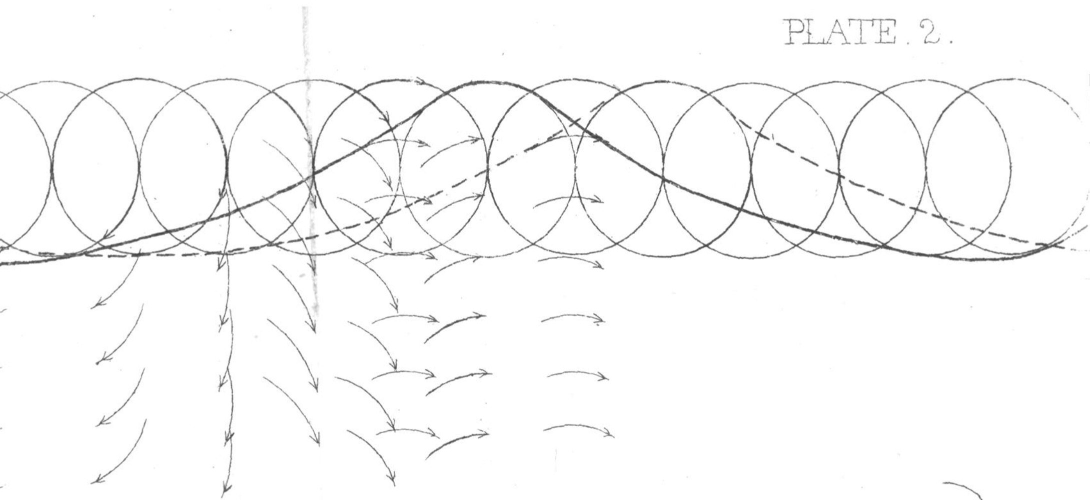
PLATE. 2.



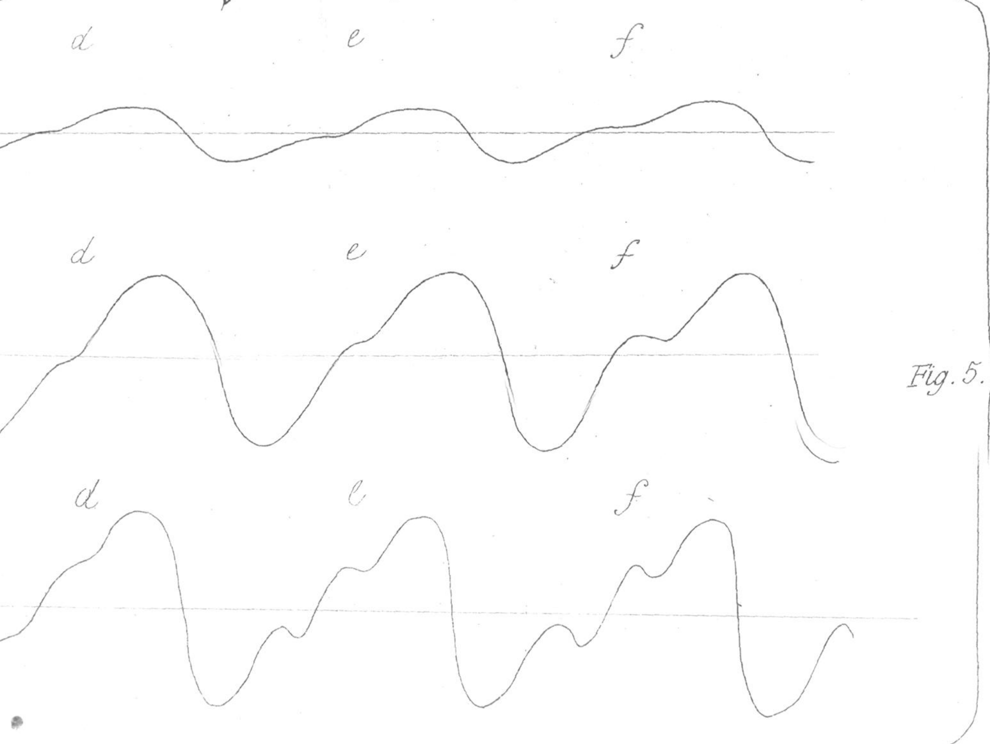


Fig. 5.

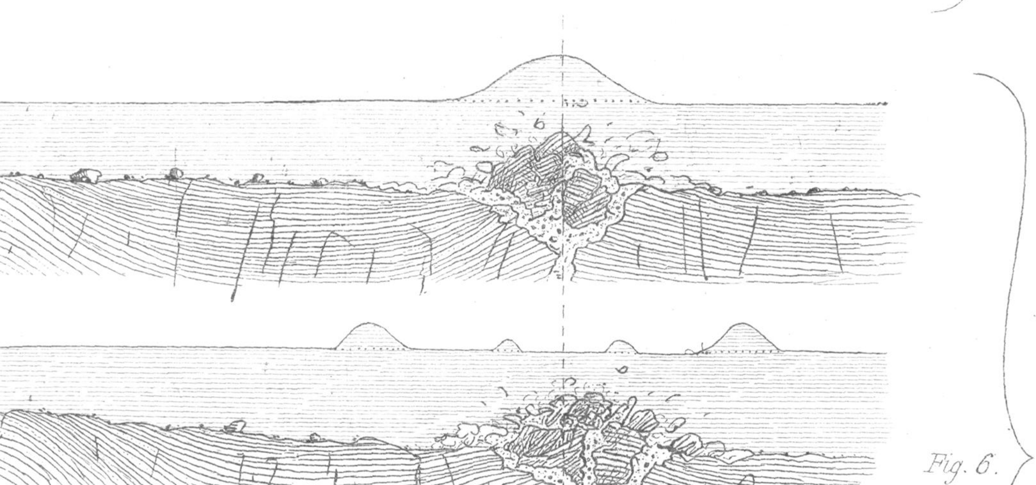
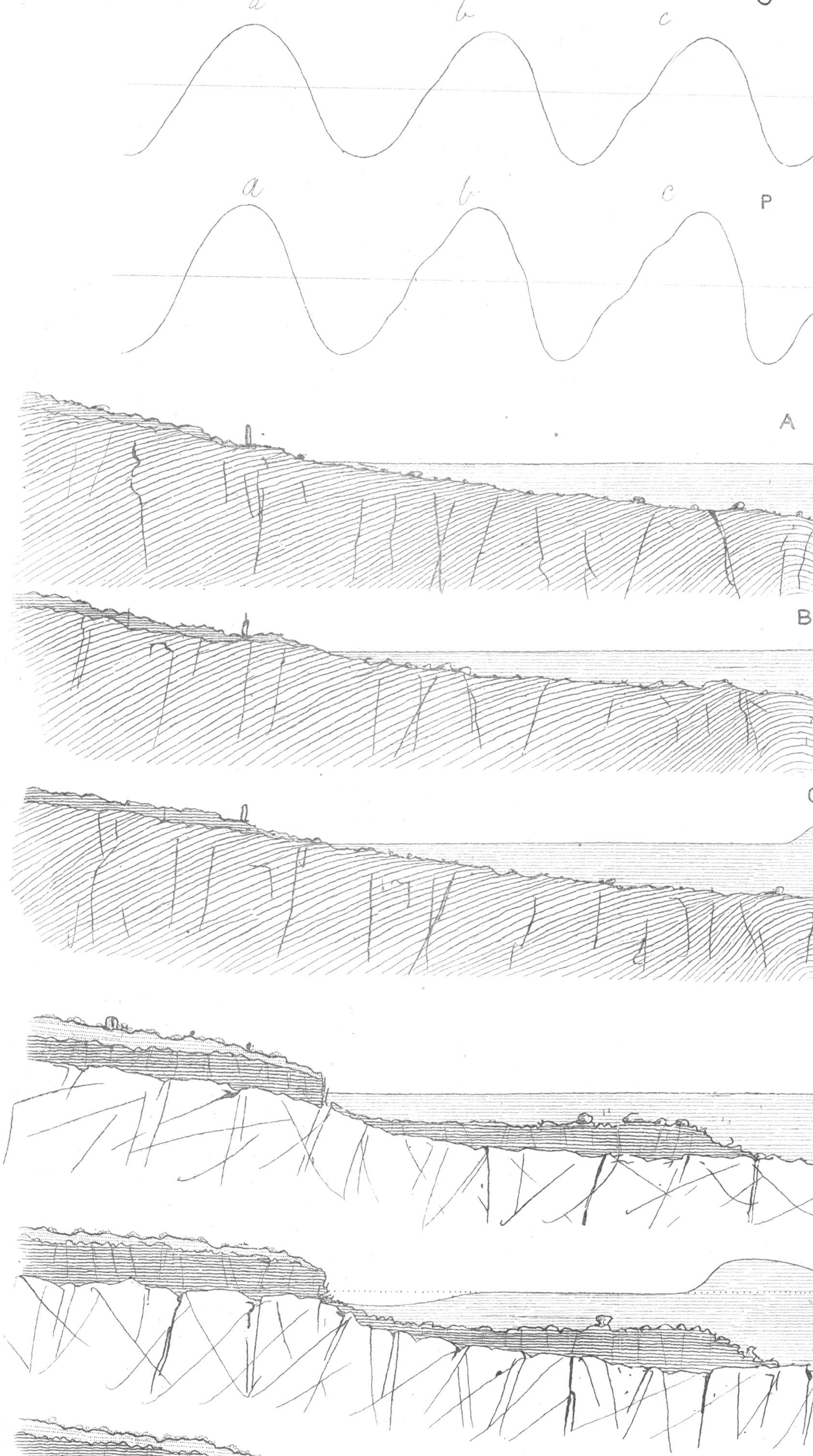


Fig. 6.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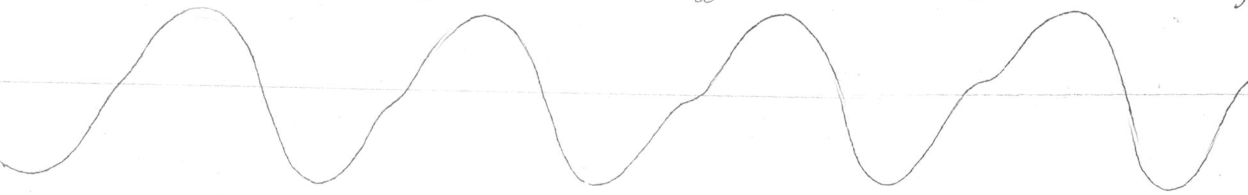

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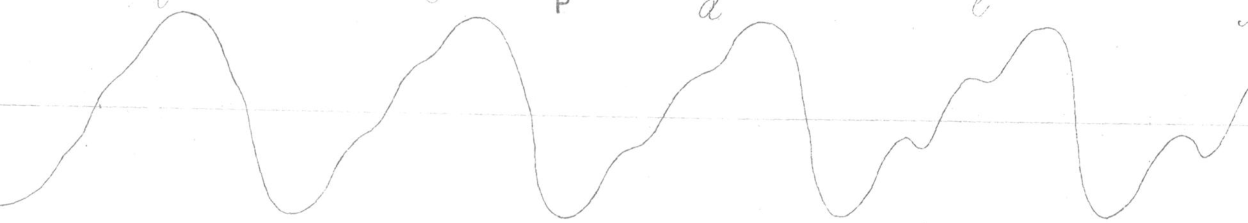

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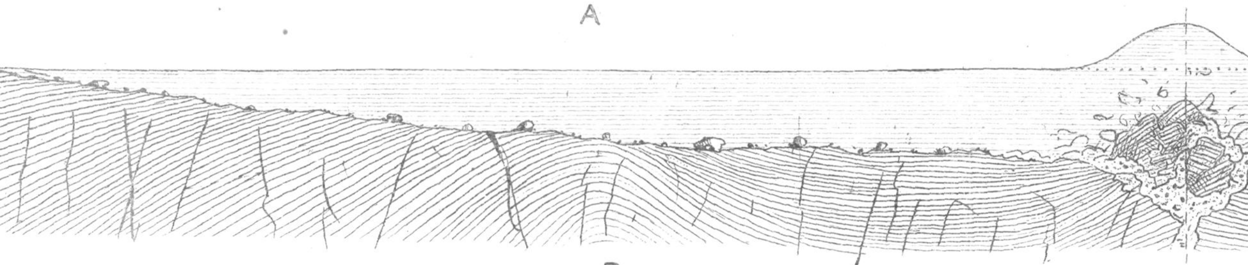

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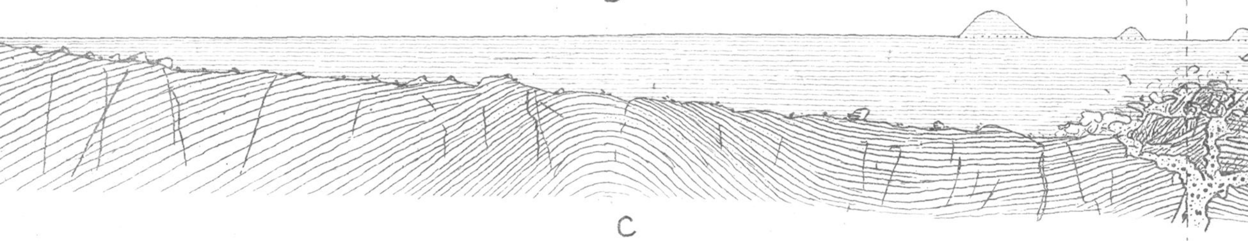

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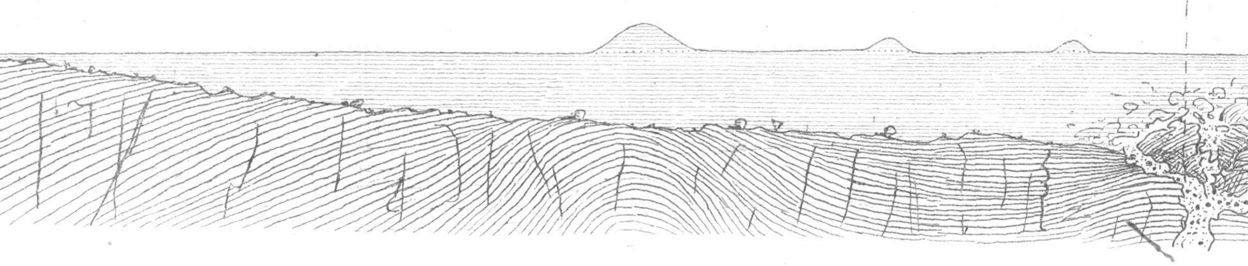

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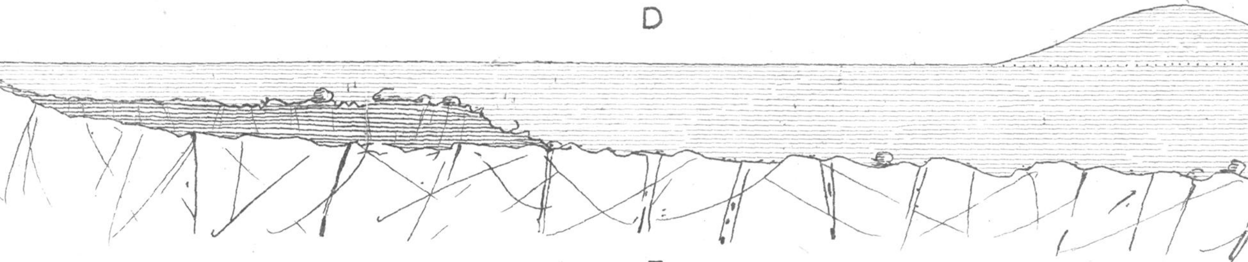

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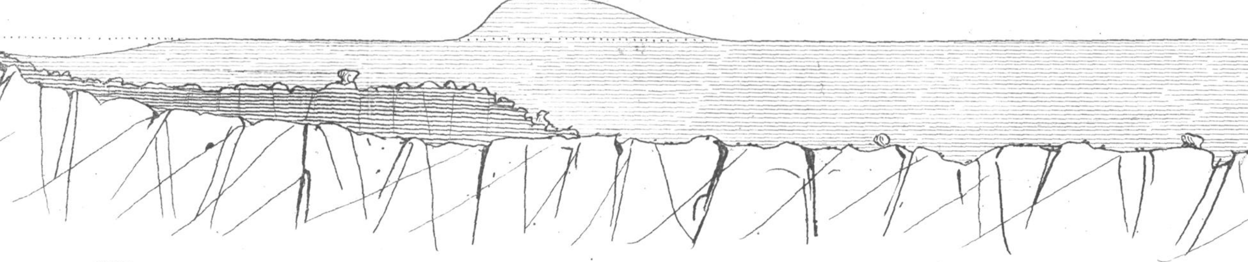

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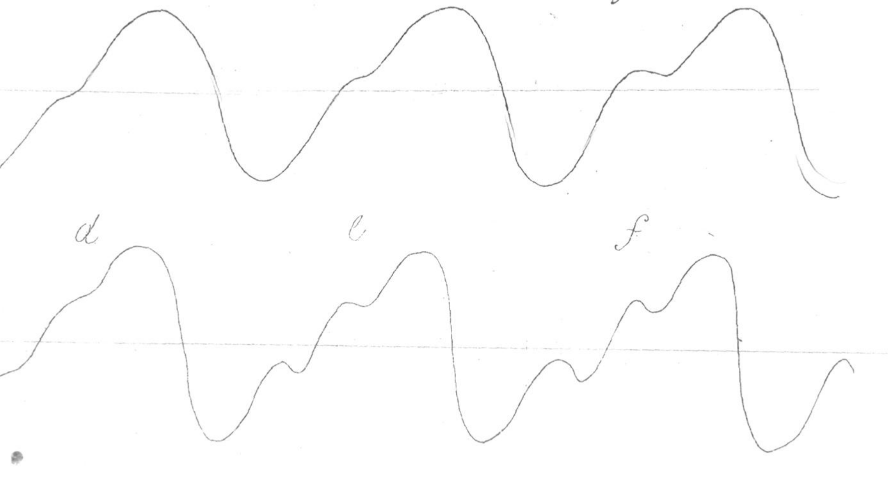

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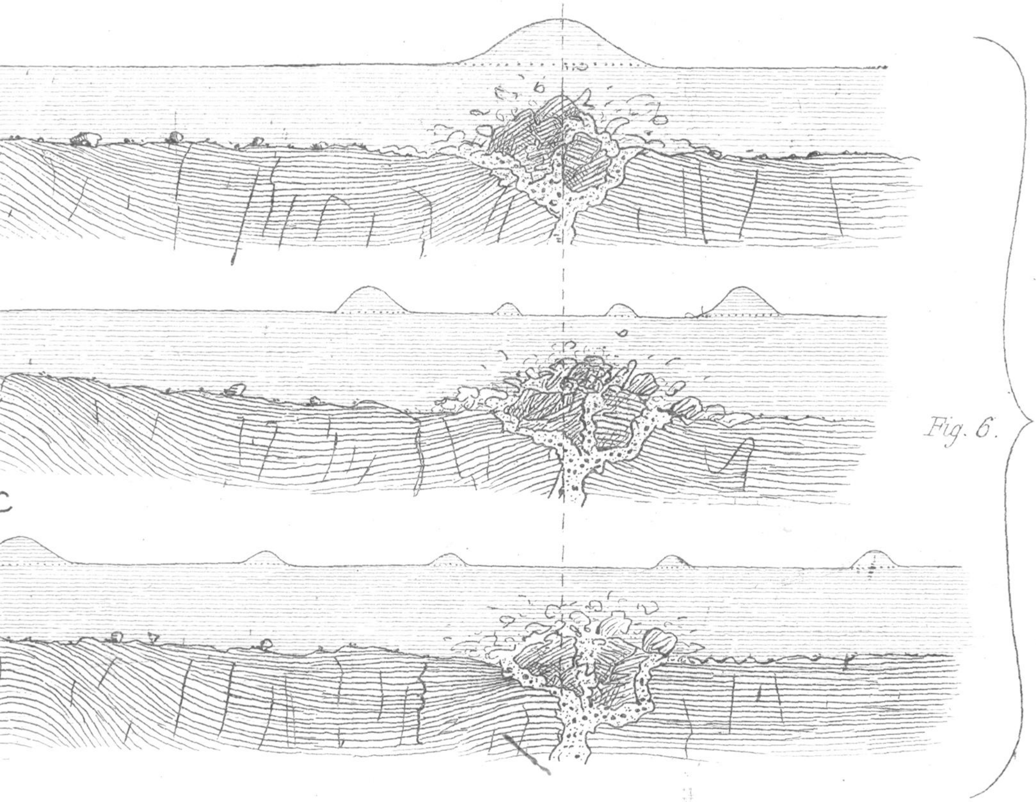

Fig. 6.

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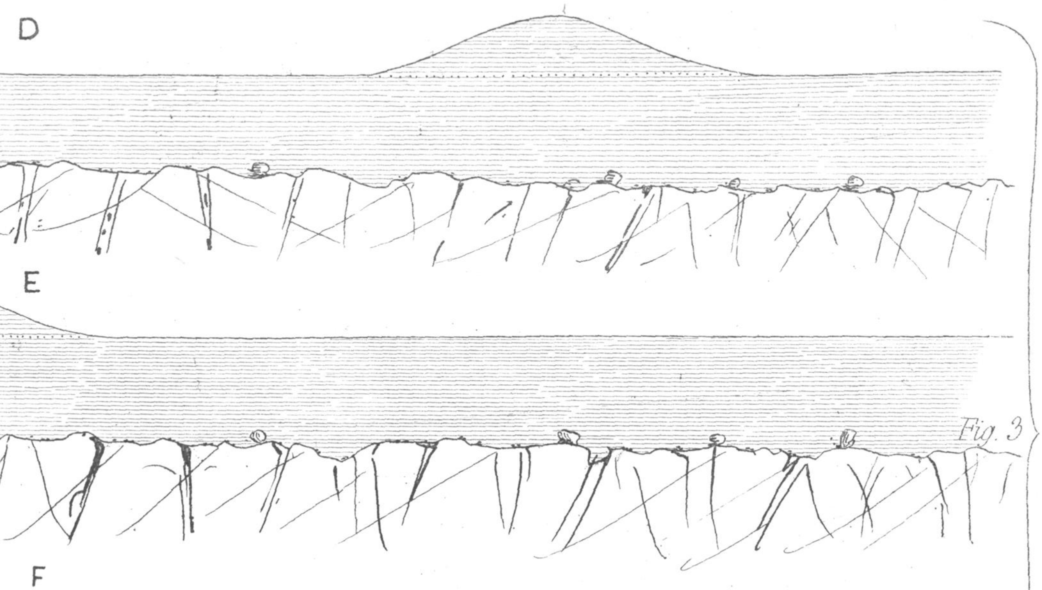
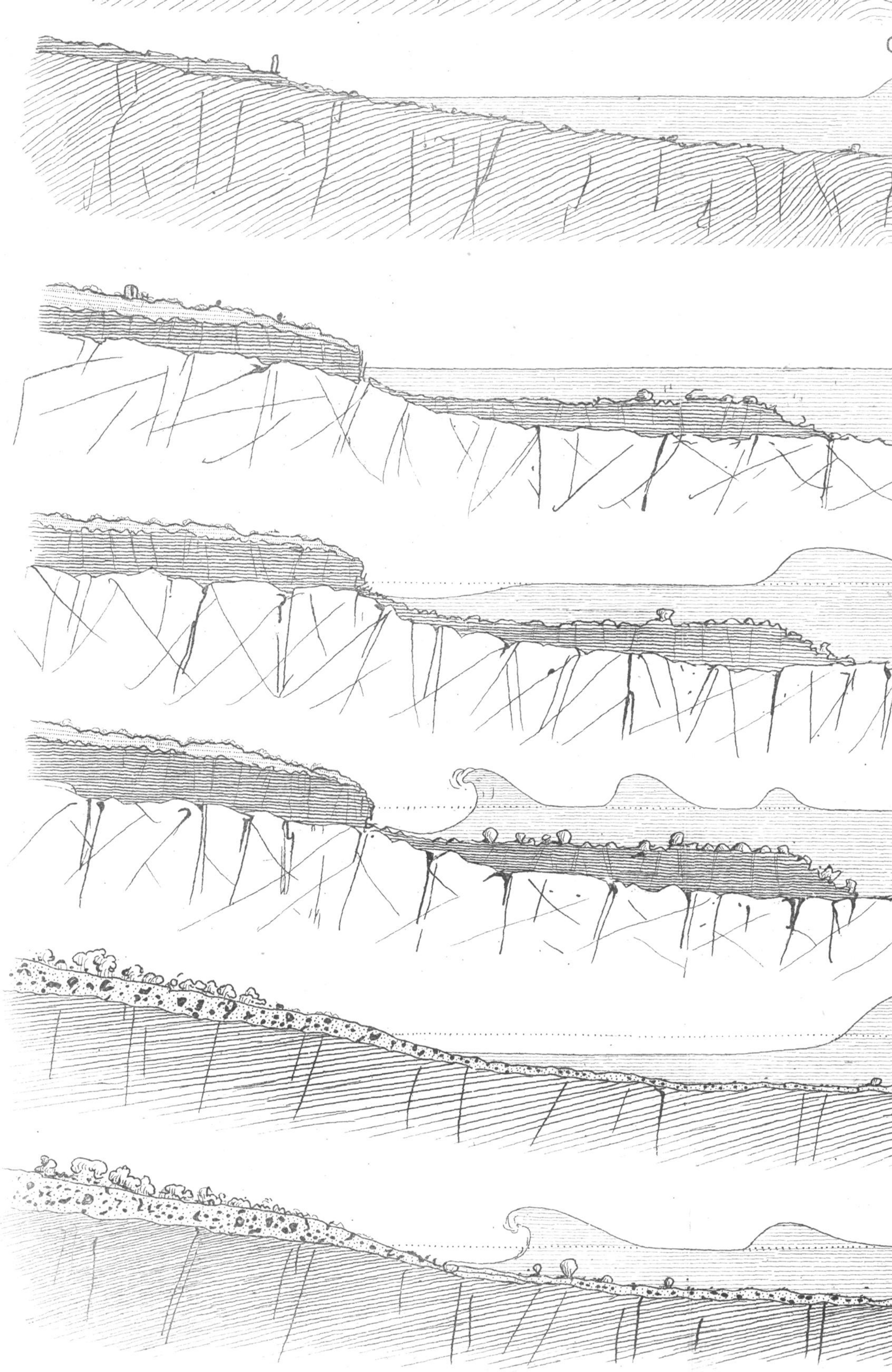


Fig. 3



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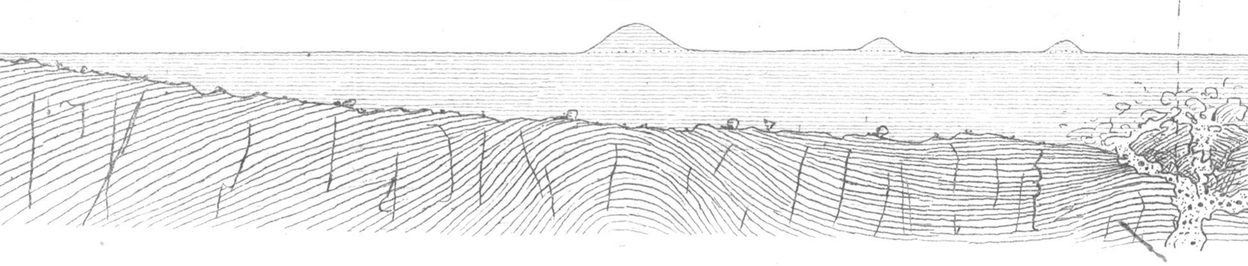

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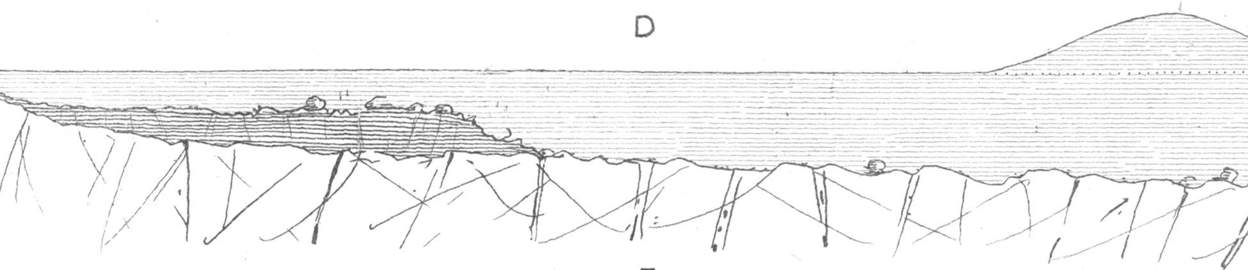

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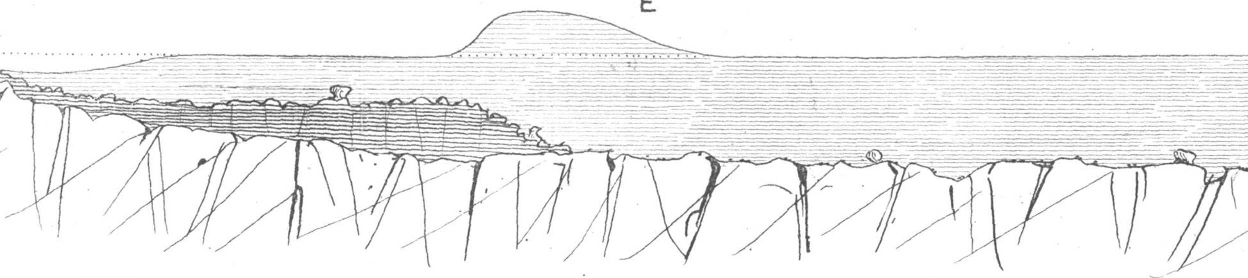

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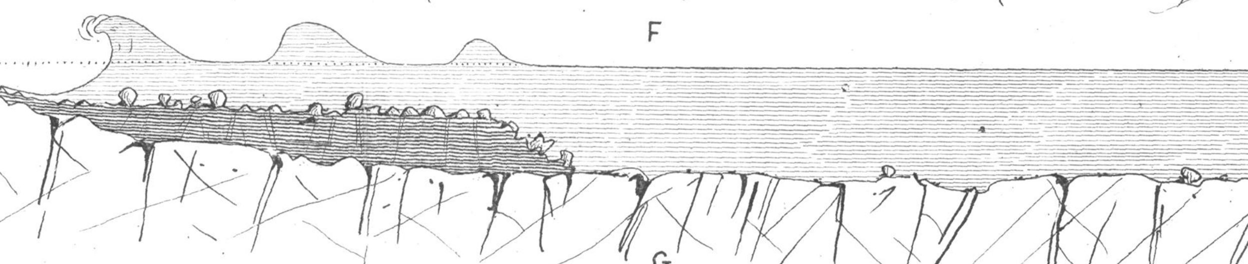

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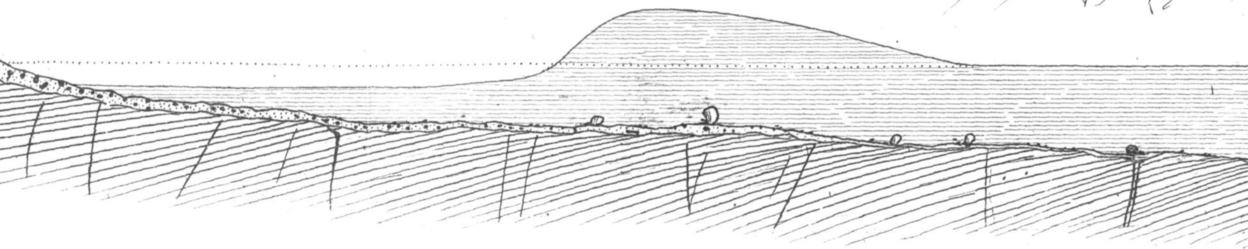

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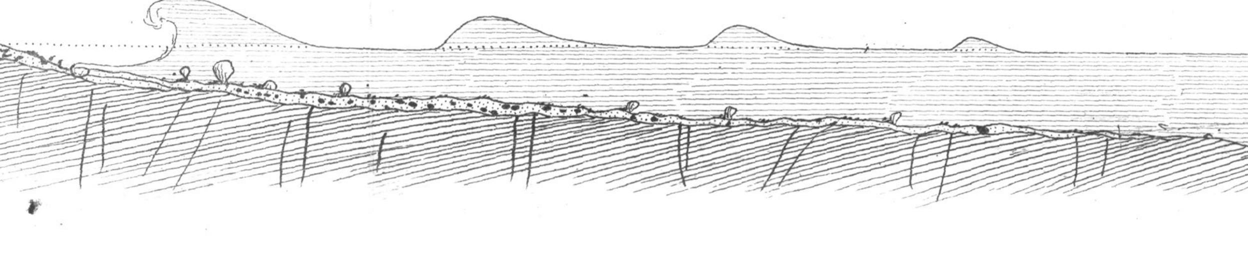
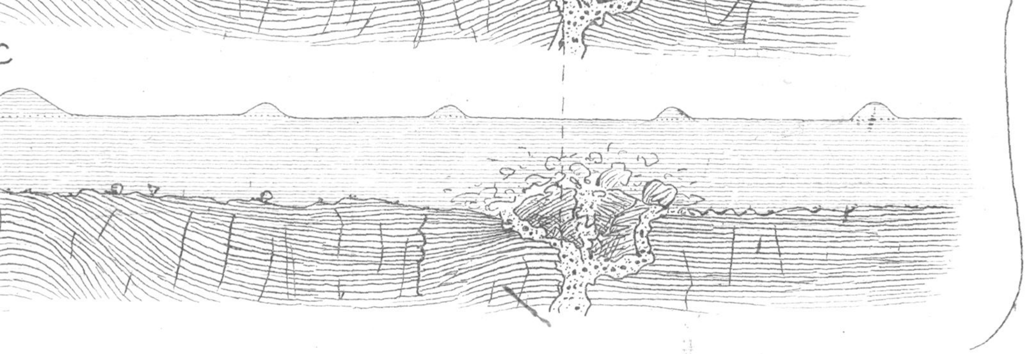




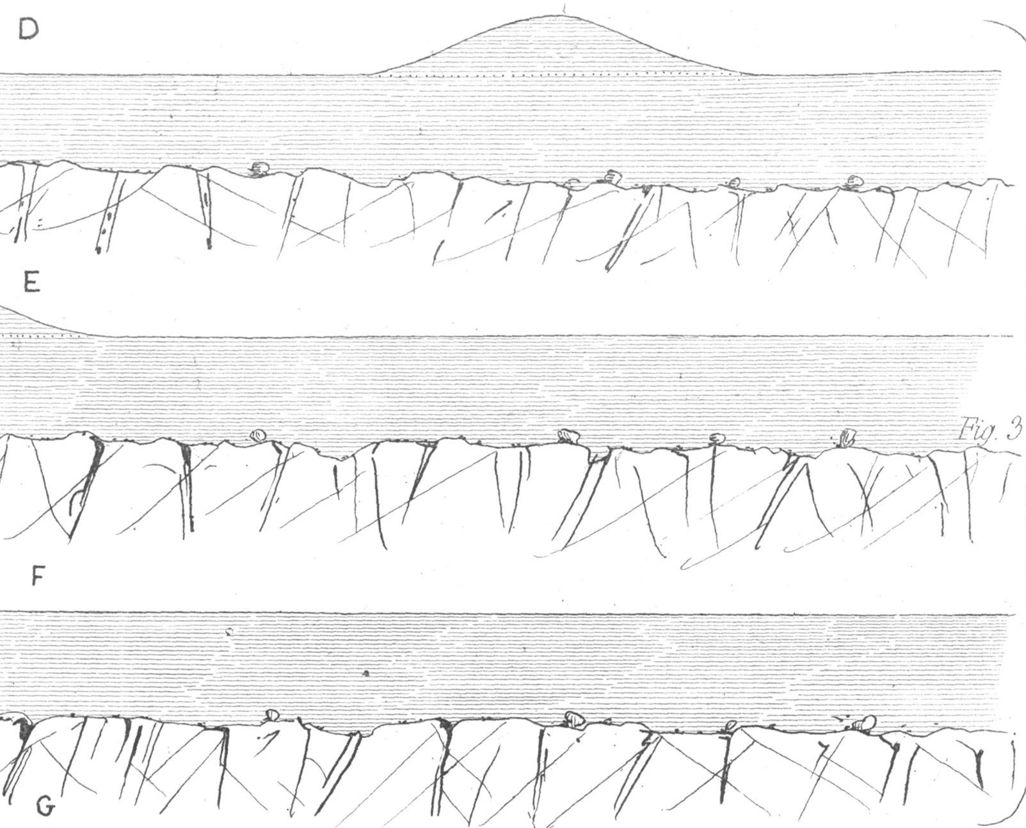


Fig. 3

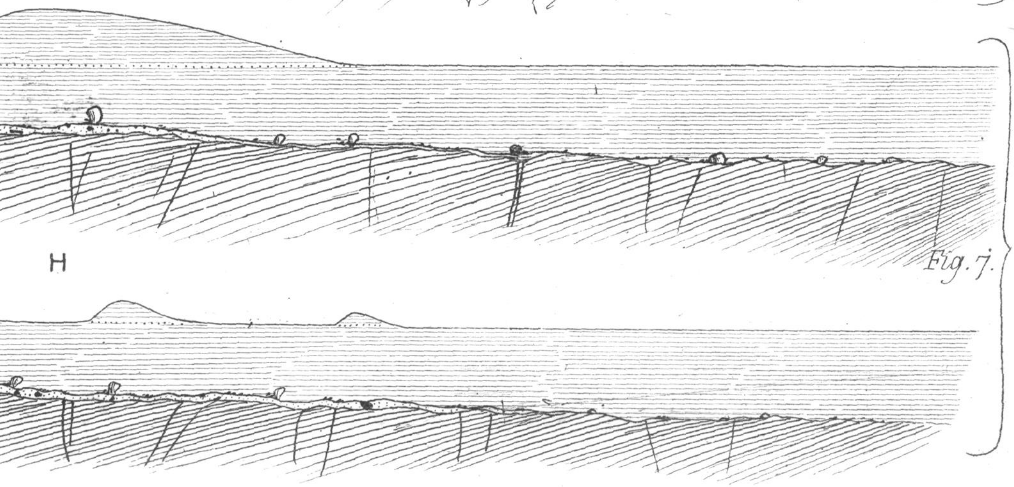


Fig. 7.

tant coast, gives no indication of whence it came, or in what direction it set out; that the great sea wave may intersect the direction of the previous earth wave or shock at any angle, or even travel in the opposite direction, as, for instance, amongst the islands of the tertiary formation, on the coast to the east of the map; and that the interval of succession between the shock and the great sea wave will vary in different localities. Thus, to the north-east of the map the shock and sea wave follow each other closely in the deep water, while at the south-west, in the shallow sea, the earth wave of interval VII. corresponds to the great sea wave of interval 13; and again, to the north-west, in the deep bay, the earth wave IX. corresponds to the sea wave 19.

The diagrams (1, 2, 3) Fig. 9, Plate II., show the variable forms which the closed curves of the earth wave cotidal lines may assume, in *the same* uniform formation, according to the nature and position of the original disturbance. Where, as in (1) this is at a single point, the curves will be nearly circular; where the disturbance is along an uniform right line, they will be ovals (2); and where the original impulse comes simultaneously from several distinct points, the curves will be irregular closed figures of contrary flexure (3). All these are subject to the changes already described in passing from one formation to another.

PLATE II.

Fig. 1. Diagram illustrative of the internal motions of a fluid wave. (Weber's Wellenlehre). The strongly marked curve is the outline of the wave in its transit towards the position shown by the similar dotted line. During the period of one phase every fluid particle in the wave has described one complete revolution, as indicated by the arrows and circles. The latter becomes elliptical in descending in a fluid of given depth.

Fig. 6. A section illustrating the origination and progress of the great sea wave by three diagrams, referring to successive short intervals from the moment of impulse by the submarine elevation or eruption. A, shows the single hillock or mass of water first elevated. In B, this has formed one great circular or oval wave, and within it a smaller one (of oscillation). In C, the further progress to land of the great sea wave is shown, and the formation of another wave of oscillation.

Fig. 3. A section showing the effects upon the great sea wave, of its coming from deep water upon a shore, which suddenly shelves by steep escarpments. In D, the great sea wave advances as a solitary mass with equal slopes front and rear over the deep sea. In E, this has just reached the edge of soundings. The front face of the wave has become steep, the rearward slope flattened, and the water at the beach is in the act of receding. In F, the solitary wave has broken into several smaller ones, having altitudes bearing relation to the shallow water beneath, and the foremost is about to form a great "breaker" upon the shore, having no longer depth to remain unbroken.

Fig. 5. The diagrams N, O, and P, are sections, showing the change of form at successive periods, *a*, *b*, *c*, &c., which a tidal or great sea wave undergoes when advancing into an estuary or bay, or into shallow water. The front and rear faces are similar, and equally sloped, while the wave is over deep water. As this shallows, the forward slope becomes steep and impending, the rearward slope flattened, then hollow; and finally the wave becomes divided into two or more smaller waves, as at *f* and *g*. N refers to a small tide or low wave; O and P to large tides or great sea waves of the largest magnitude.

Fig. 7 illustrates the phenomena presented by the great sea wave, on coming in shore upon a gently sloping beach, which has uniformly shallowed from the deep sea. The wave here comes in solitary and unbroken, but with a steep and impending front. When advanced to G, a great recession of water from the beach occurs. Advancing still further, as in H, the shallowness of the water divides the wave, and it falls in a succession of breakers upon the land.

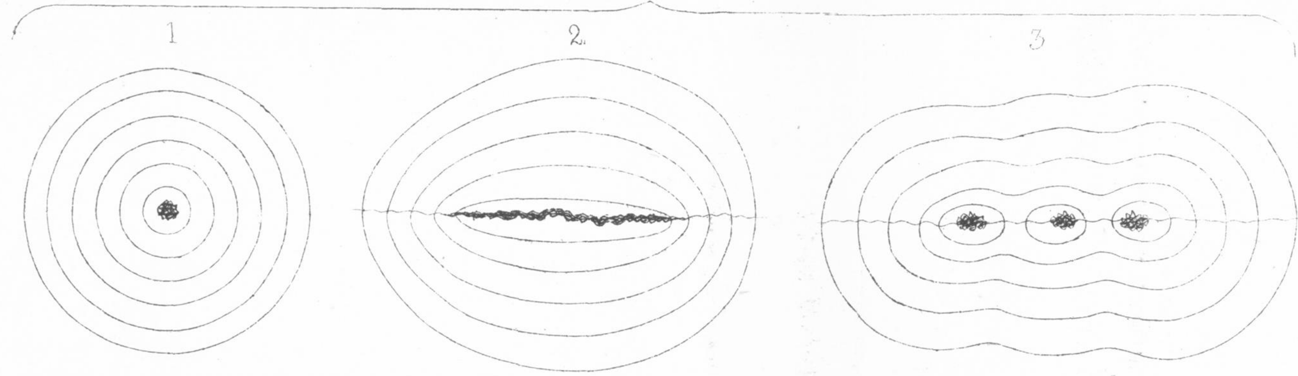
Comparing Figs. 3 and 7, it is obvious that the most violent and destructive sweep on land, of the great sea wave, will occur in circumstances, where the depth of water, close in to the land, is *just sufficient* to carry in the wave as one solitary unbroken mass, with a steep and impending front. If the water be profoundly deep close to land, and the latter "iron bound," the wave comes in with both slopes alike, and does little or no damage.

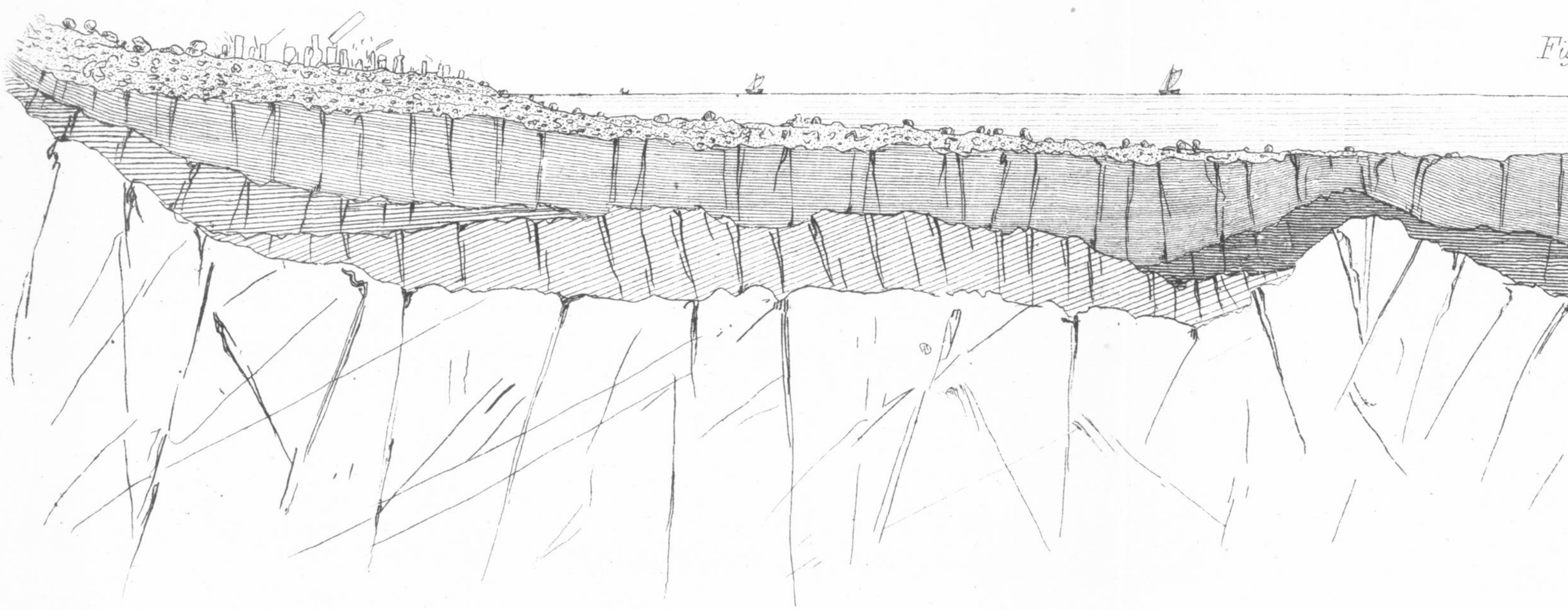
Plate III.

Fig. 2. A section showing the general relations of the earthquake phenomena in their successive occurrence. A submarine eruption has just taken place. The earth wave and forced sea wave have just arrived at land, marked by a tower falling upon the shore. The shock has passed the ships at sea, but the great sea wave and its minor successors have as yet not reached them, on their way towards the land.

Fig. 4 is intended to explain the apparent recession of the sea, at the moment that the forced sea wave arrives at the shore with the earth wave or shock. In the section L, the undulation of surface of the earth wave or shock is shown (much exaggerated) passing along the bed of the sea, which is here shallow, and carrying along upon its crest, and with its own velocity, the small aqueous undulation, or heap of pushed up water, denominated "the forced sea wave." In the diagram M, the undulation of the earth wave has just reached the shore, has elevated the beach, at the ordinary tide-mark by a height equal to its own, and, therefore, has apparently depressed the surface of the water at this point by the same amount. The earth wave here leaves the small forced sea wave behind it, and the latter breaks and falls in small breakers, or ripples, upon the beach.

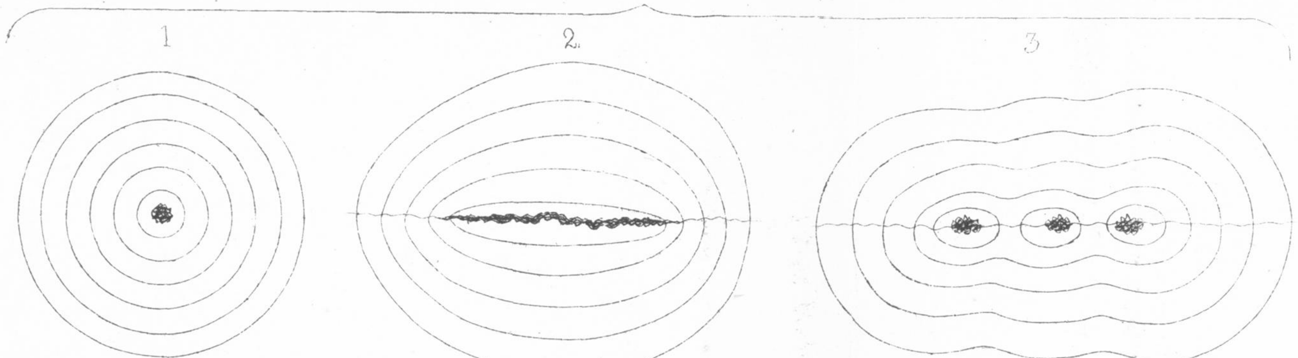
Fig. 9.





a

Fig. 9.



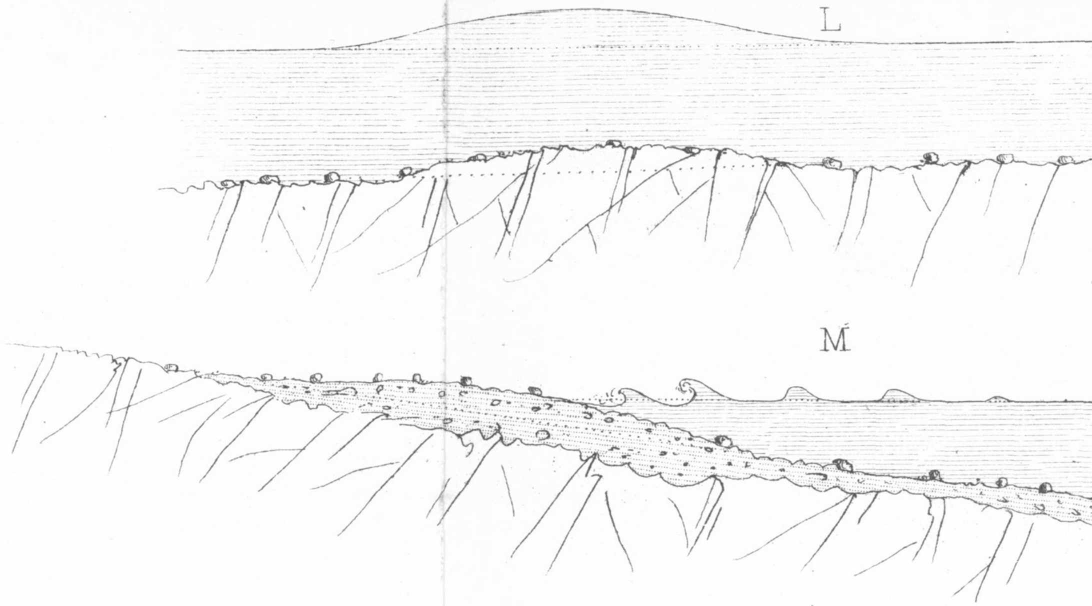


Fig. 2.

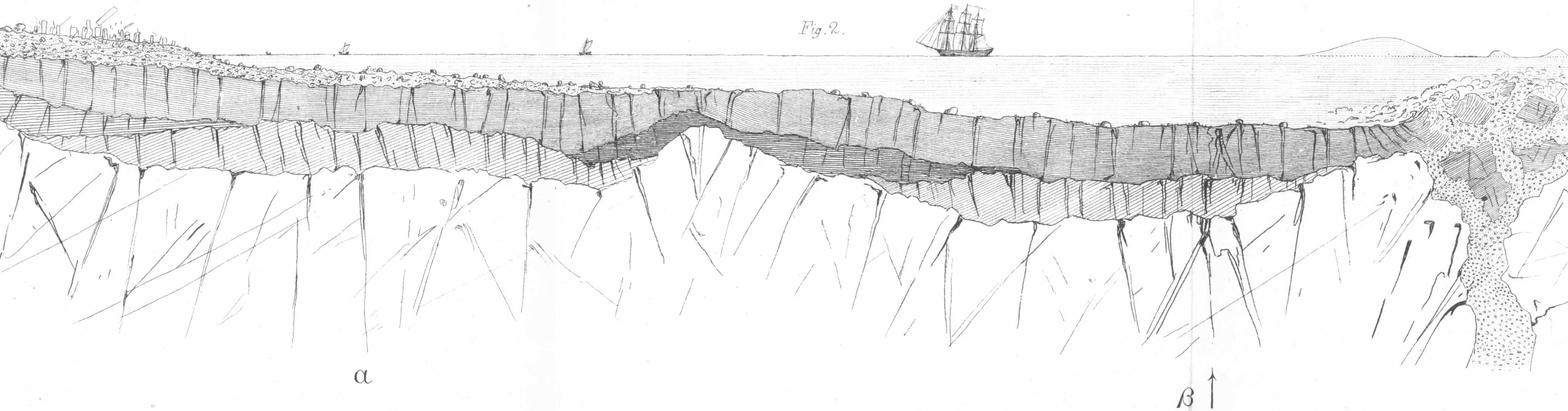


PLATE III.

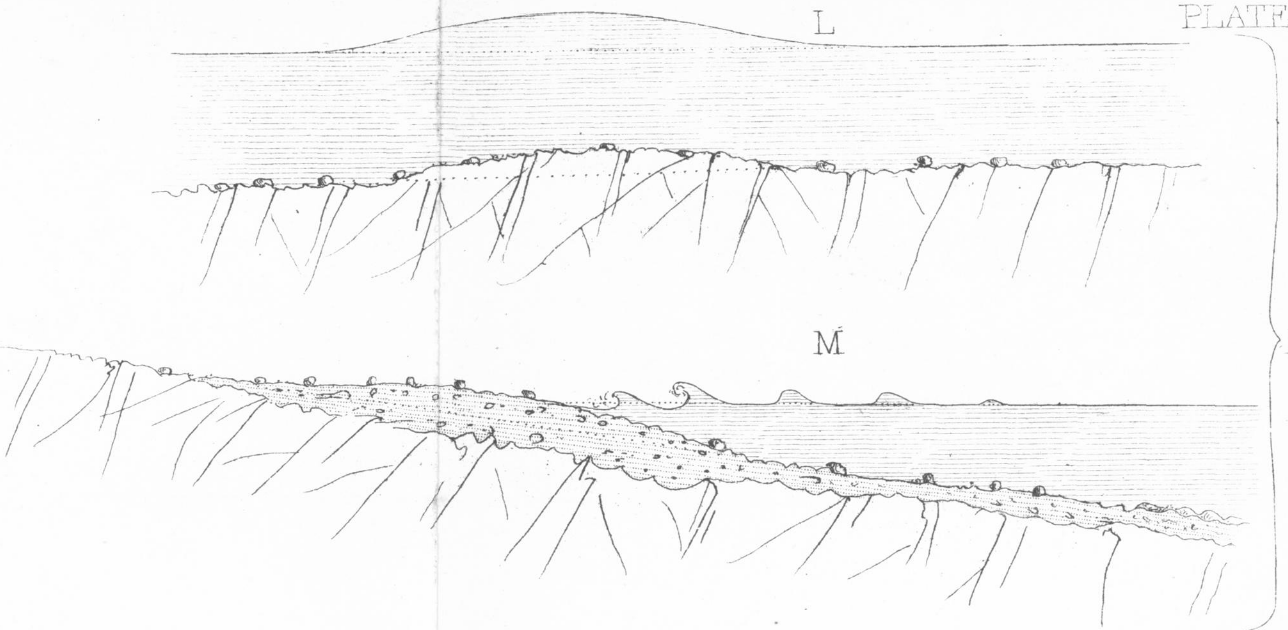
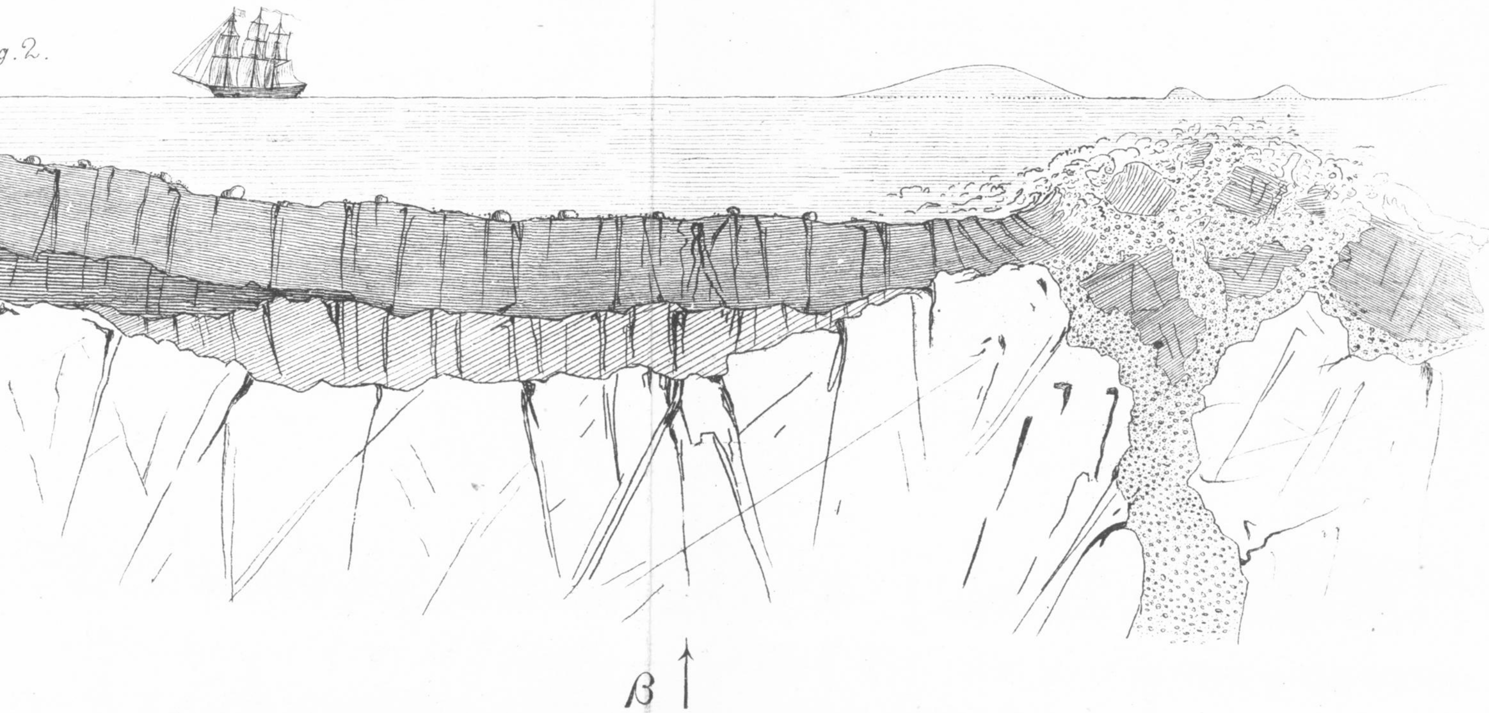
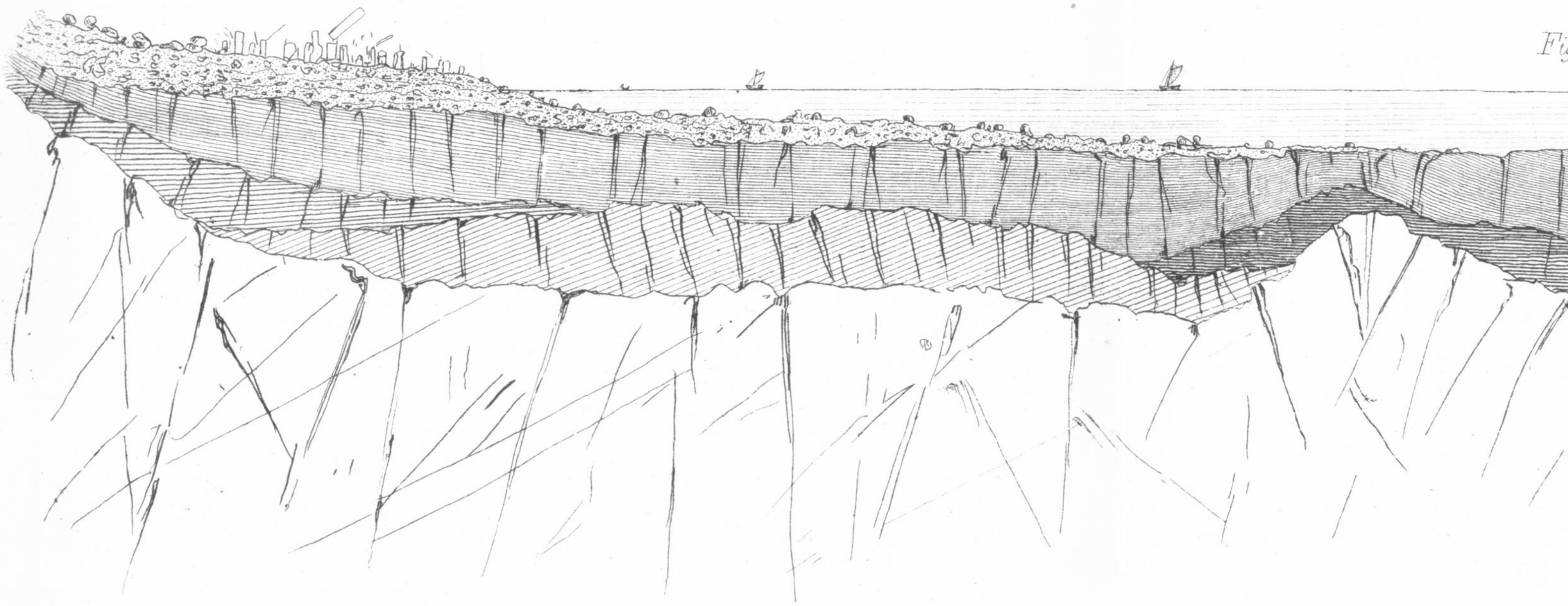


Fig. 4.

g. 2.



Fig



α

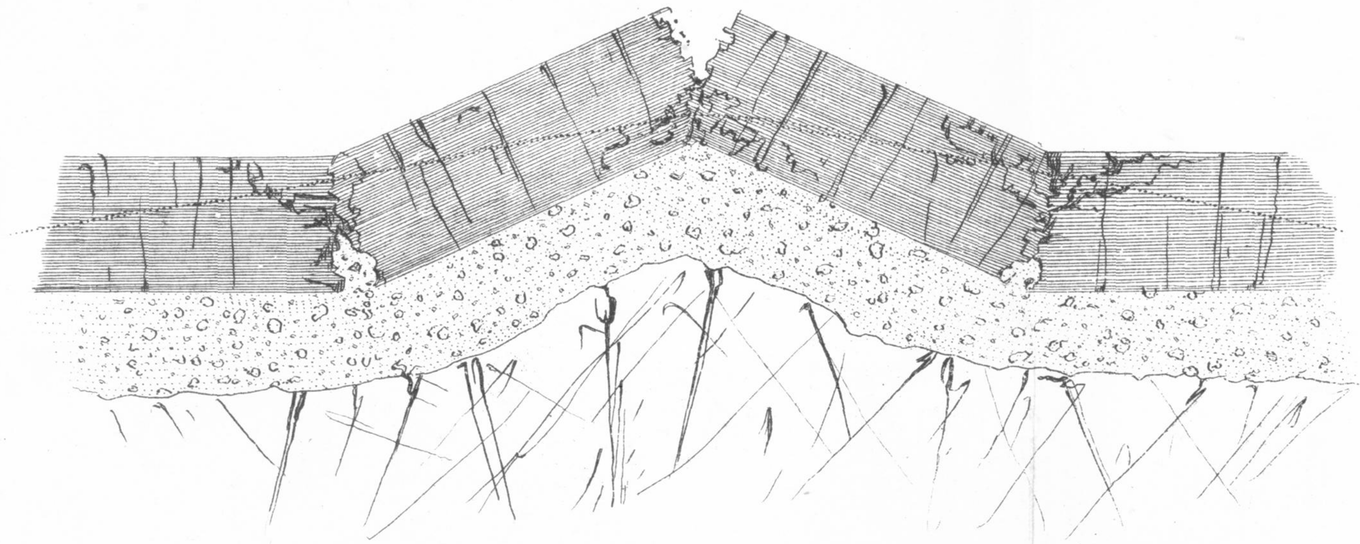


Fig. 8.

γ

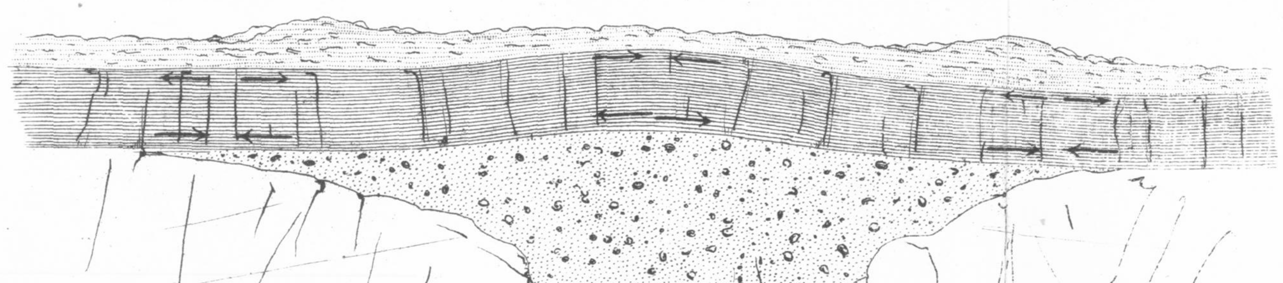
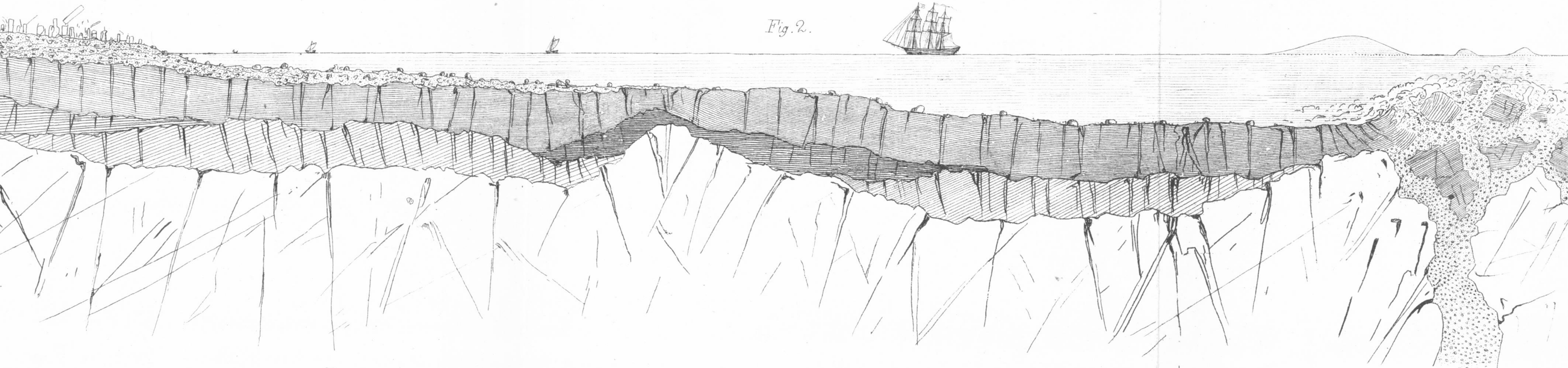


Fig. 2.



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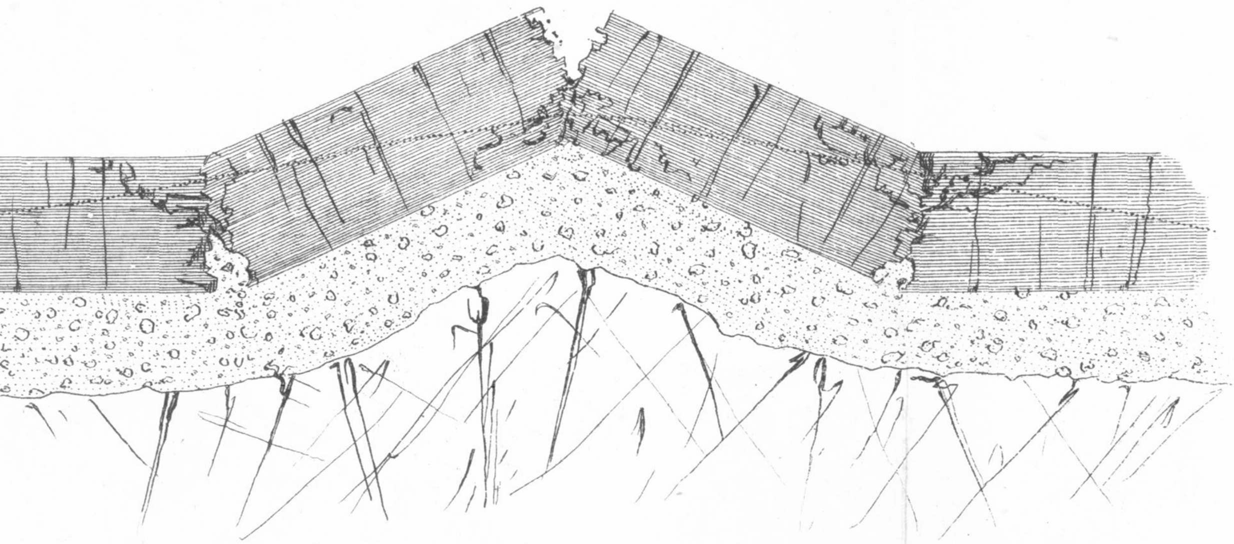

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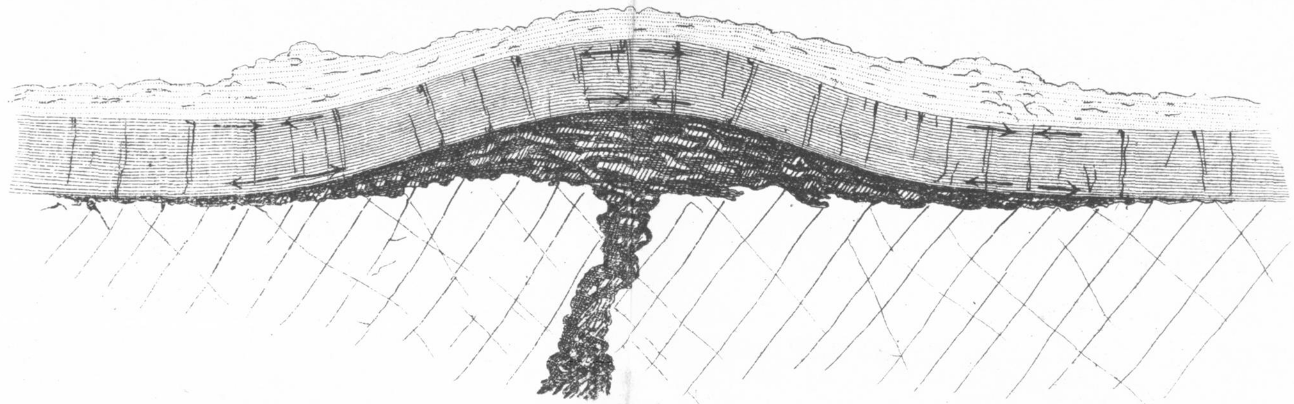
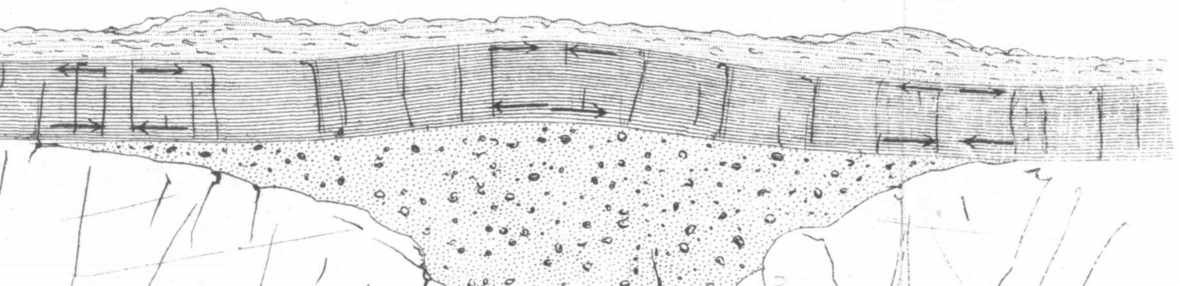


Fig. 8. α. β. γ. δ.

γ ↓



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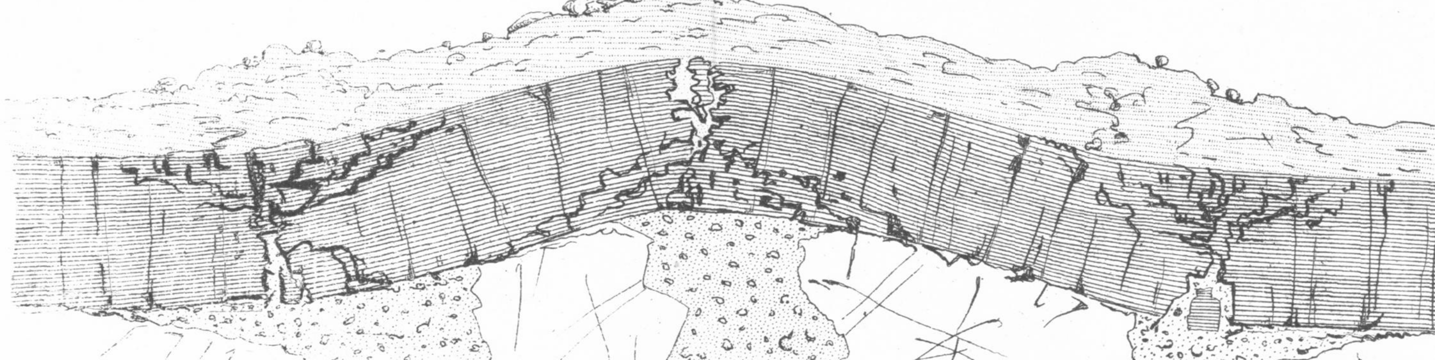
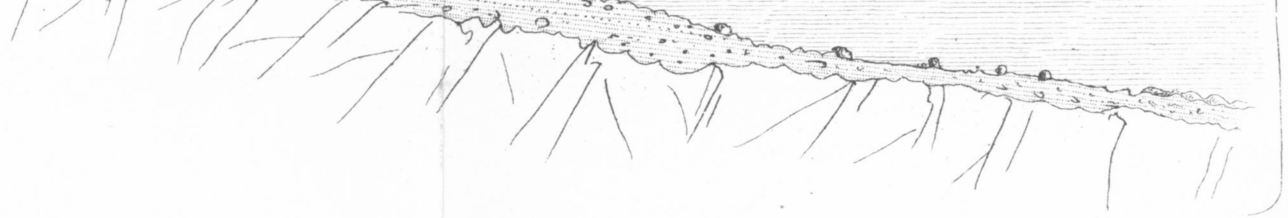
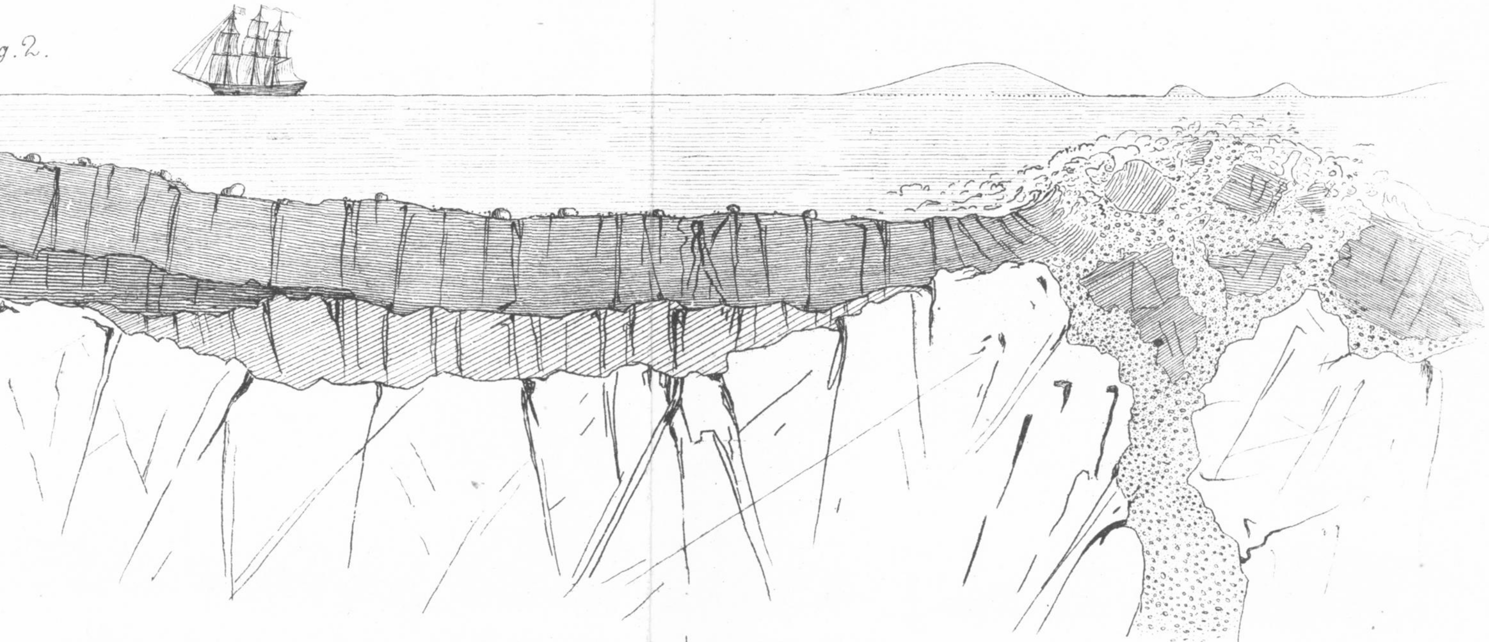
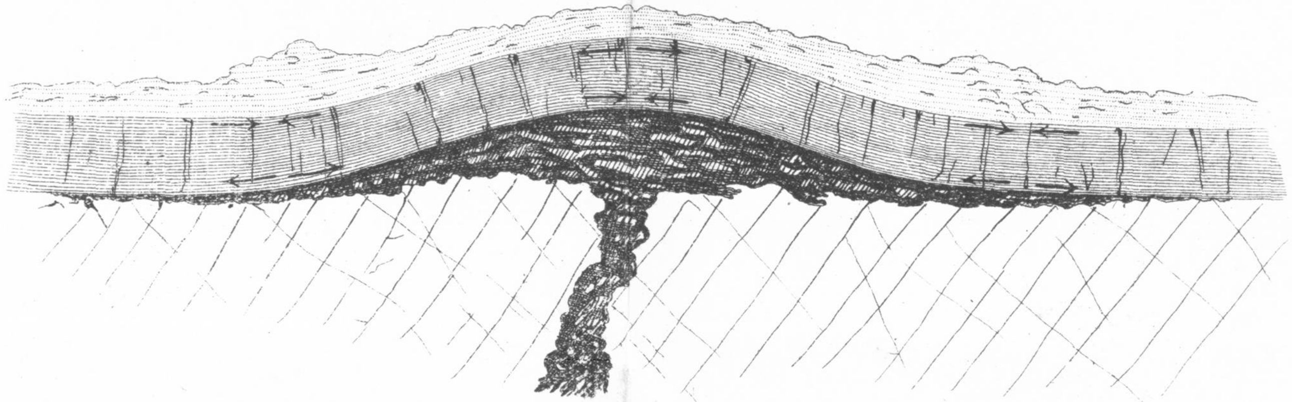




g. 2.

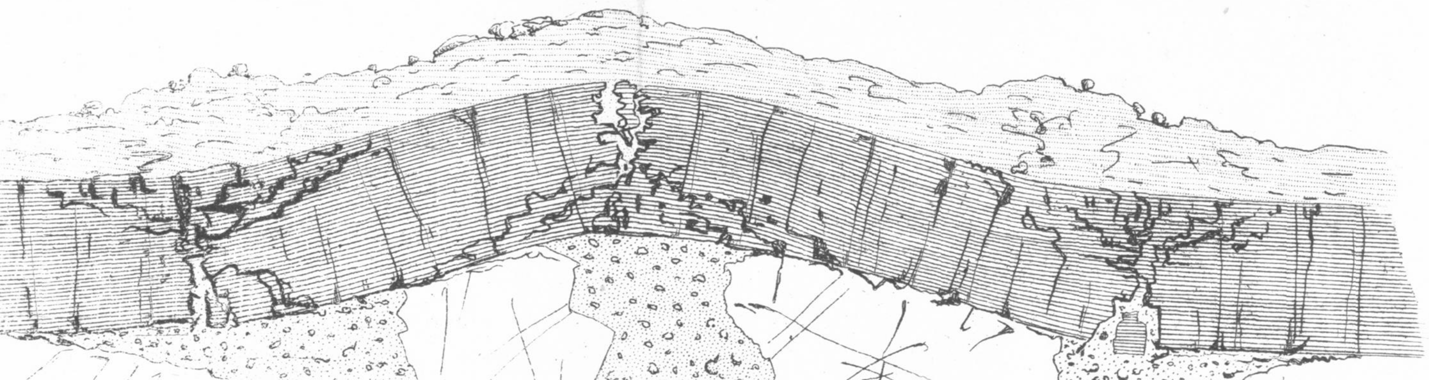


β



a. β. γ. δ.

δ



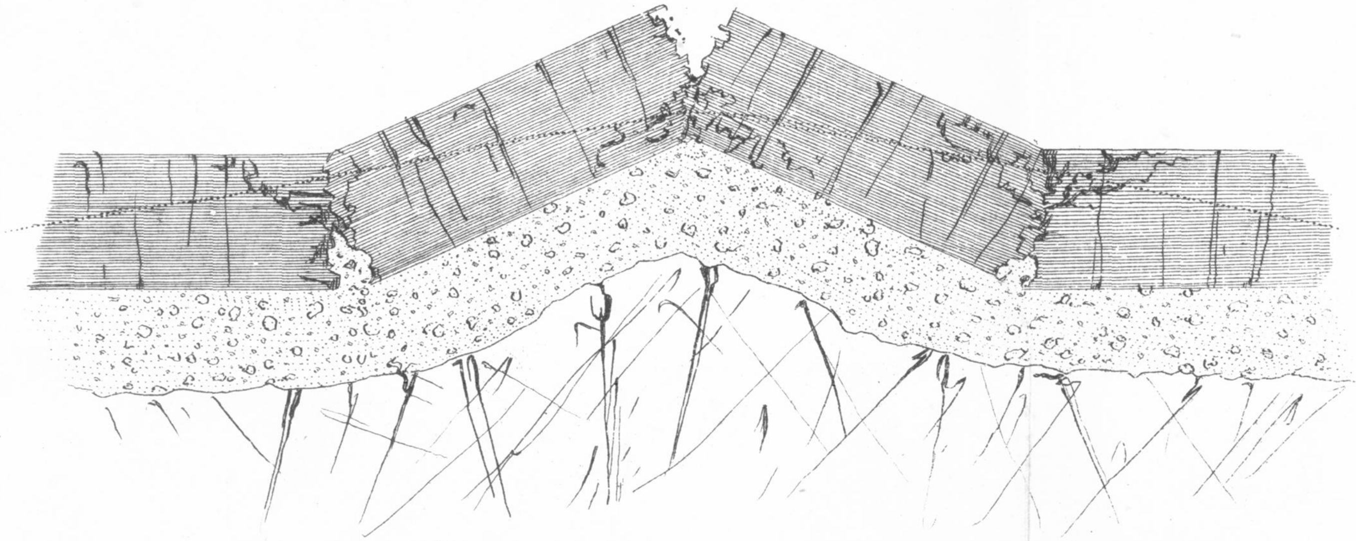
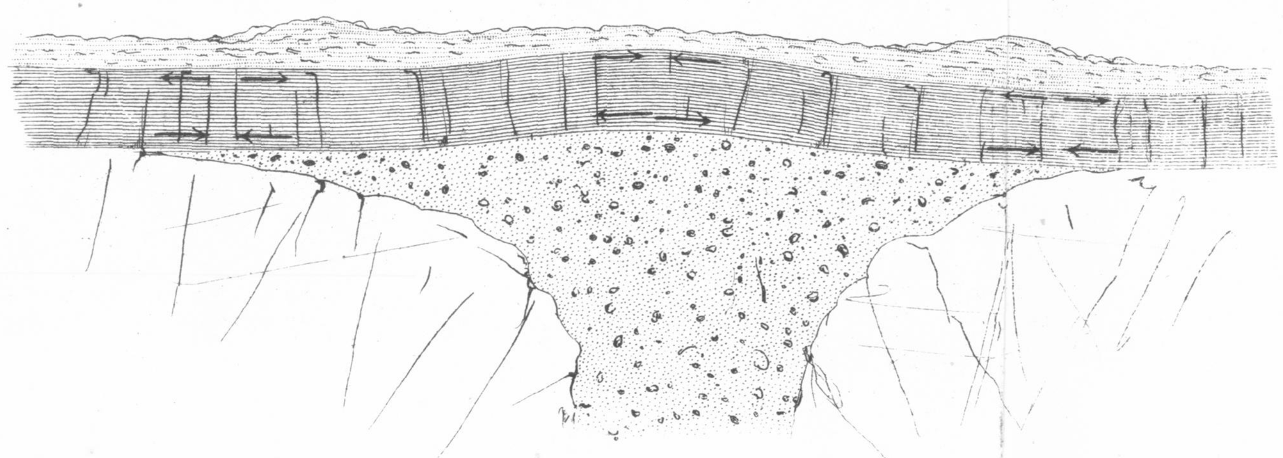
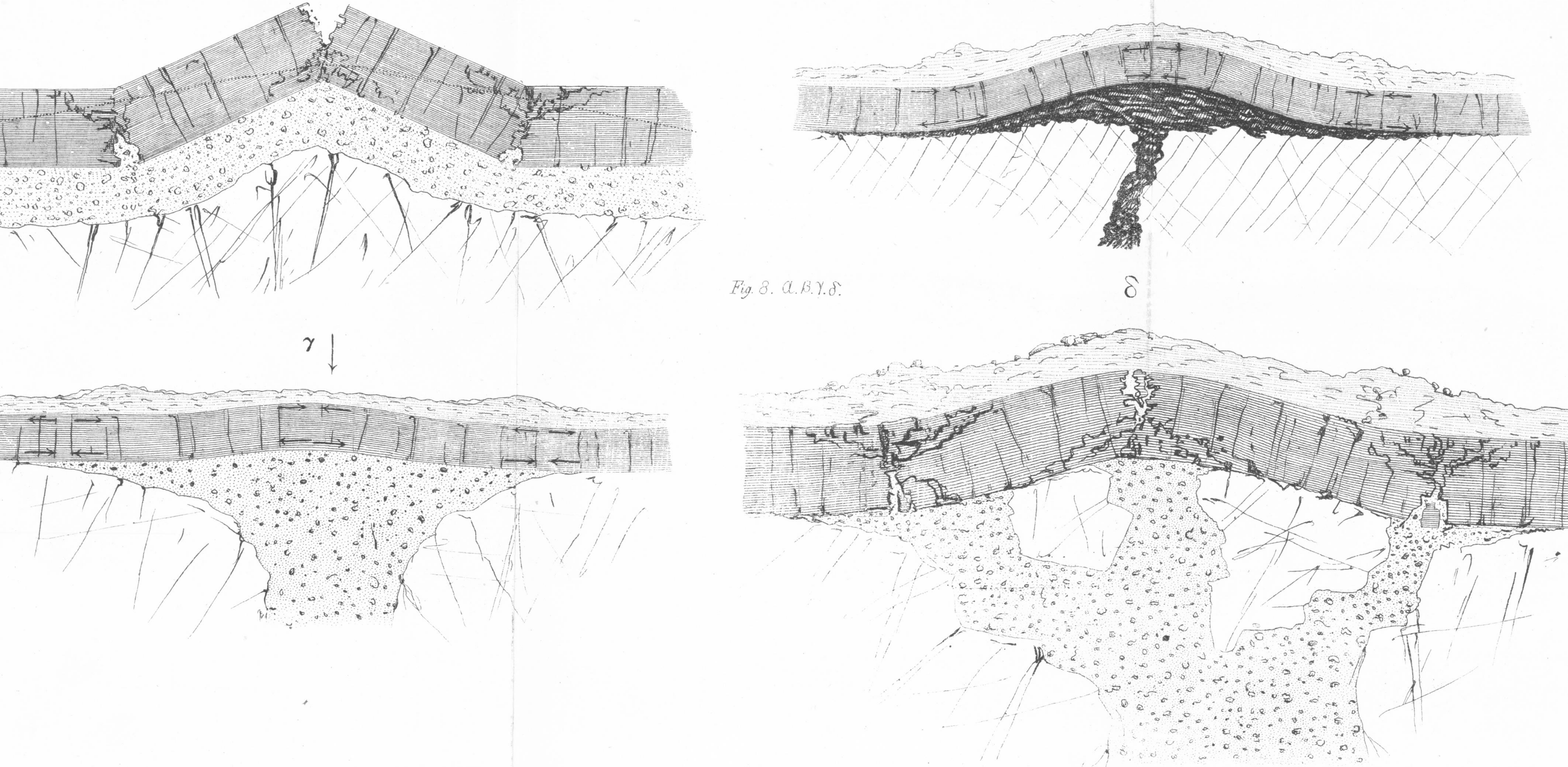


Fig. 8.

γ





γ

δ

Fig. 8. α.β.γ.δ.

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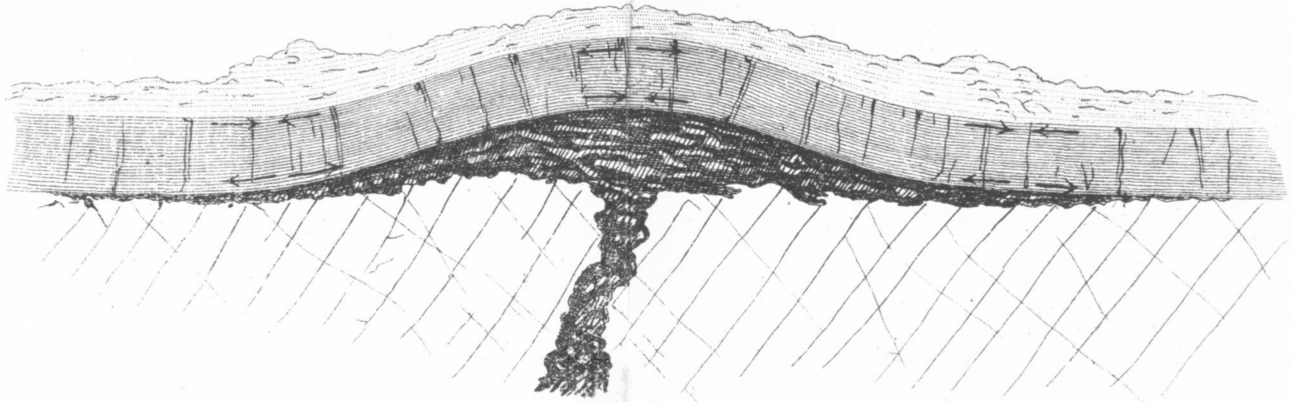
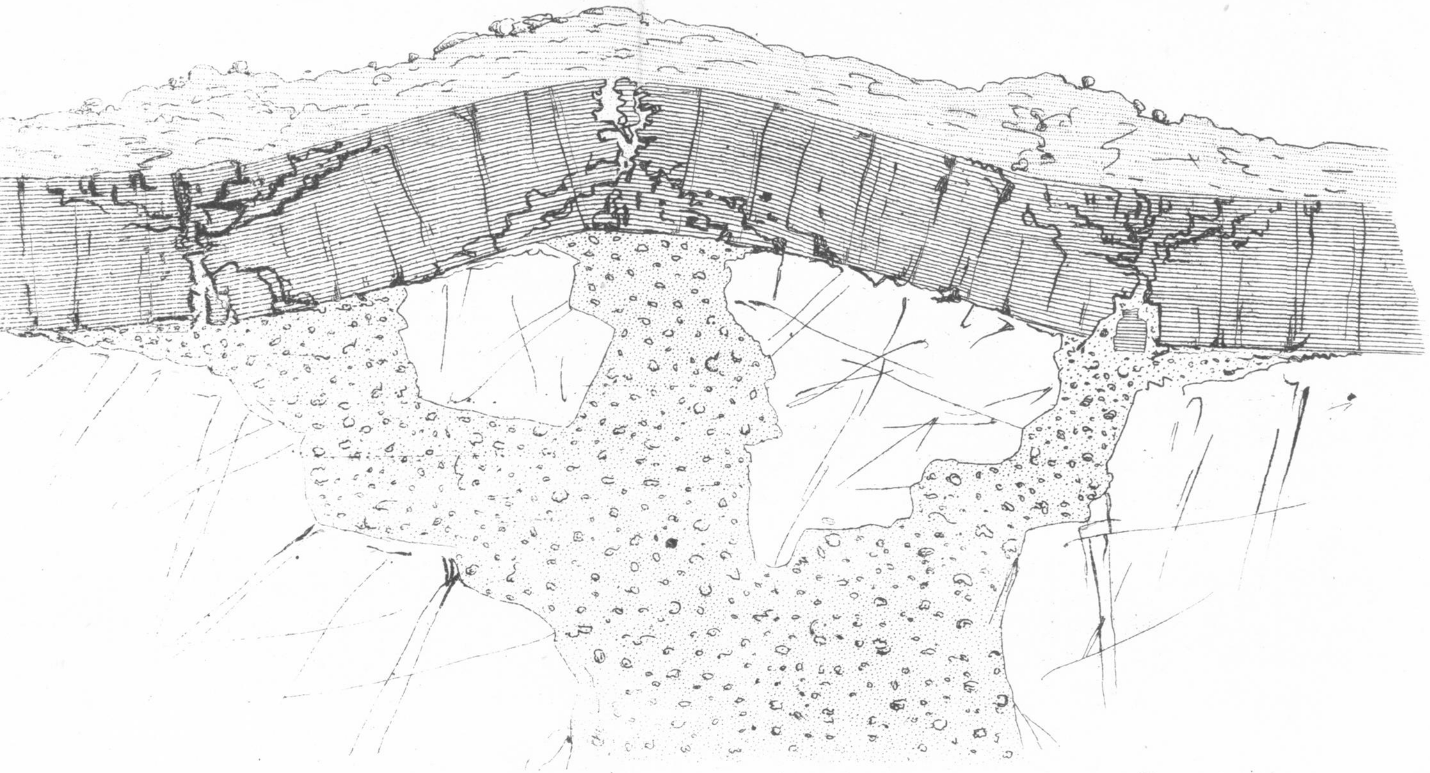


α.β.γ.δ.

δ



Etched by W. Mc Dowall.

Fig. 8 shows, by four diagrams, the nature of the forces of extension and compression, and the directions of the elastic waves produced either by flexure or fracture.

In β, the mass of stratified formation is in act of being elevated by the protrusion of lava from beneath, carrying up the loose materials reposing upon it. The arrows above and below the neutral plane indicate the directions of the compressions and extensions, and hence of the transit of elastic waves, if the flexure be of sufficient extent and rapidity to produce such. In γ, a similar stratified mass is supposed to be in progress of subsidation, and the arrows show that all the previous forces remain operative, but changed in direction. In δ, the flexure has been attended with fracture, and earth waves have passed outwards in all directions, and the diagram shows the directions of compression produced by the wedging together of masses of rock in progress of being lifted or tilted over, by continued upheaval after previous fracture, by which minor earth waves, subsequent to the great shock, may be propagated.

Fig. 9 has been explained in referring to the map of cotidal lines, Plate I.